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No. 8

WINDMILLS FOR IRRIGATION.—MURPHY

WASHINGTON
GOVERNMENT PRINTING OFFICE
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UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

WINDMILLS FOR IRRIGATION

BY

EDWARD CHARLES MURPHY

WASHINGTON

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LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Division of Hydrography,
Washington, April 13, 1897.

Sir: I have the honor to transmit herewith a manuscript entitled Windmills for Irrigation, by E. C. Murphy, professor of civil engineering in the University of Kansas, at Lawrence. This gives the results of experimental tests carried on during the summer of 1896 upon windmills located for the greater part in the vicinity of Garden, Kansas. These results are presented in condensed form for early publication in order that they may be available for use and discussion by persons interested in the matter. They should be considered as preliminary to a more popular presentation, which, however, can be given only when a considerable number of experimental measurements of various kinds have been completed and a careful study yielding general conclusions has been made.

In detailed work of this character it is impossible to avoid technical discussions and mathematical formulas, but as far as possible the results of the tests have been expressed in graphic diagrams. A careful study and comparison of these and of the accompanying descriptions shows the difference of behavior of the mills examined under the conditions in which they were found. It is, of course, impossible to draw conclusions applicable to all mills from the examination of a few, but the facts here shown are significant and worthy of careful consideration.

Very respectfully,
F. H. Newell,
Hydrographer in Charge.

Hon. Charles D. Walcott,
Director United States Geological Survey.

WINDMILLS FOR IRRIGATION.

By E. C. Murphy.

INTRODUCTION.

The windmill has long been employed to perform mechanical work. Just when and where the first windmill was used is not definitely known, but we know that a considerable number were utilized in France in the twelfth century. They were employed in Holland in the fifteenth century in pumping surface water over the dikes into the sea. It is not the purpose of this paper, however, to trace the history[1] or development of windmills, but to present the results of some recent measurements on the useful work windmills are doing, especially when employed to pump water. It is surprising to note how little definite information there is in regard to the efficiency of windmills, especially of the steel back-geared mills of the present day. Thousands, perhaps hundreds of thousands, are in use doing work of various kinds, and yet very few careful measurements have been made to determine their horsepower or the number of foot-pounds of work they are accomplishing under different velocities. It was to supply in a measure this lack that in 1895 the writer undertook to measure, with instruments then at his disposal, the pumping power of windmills. In 1896, with much better facilities, he continued this work, extending it to include power as well as pumping mills. The attempt was not made to measure the power of every make of mill; that was impossible. It was thought best to confine the work to different sizes of the standard mills, those that are used to a large extent and are giving satisfaction. In some cases two or three tests of the same size and make of mill were made for the purpose of showing the influence of the pump or well on the useful work done.

Perhaps nowhere in the United States is irrigation from wells by the use of windmills so extensively practiced as in the vicinity of Garden. Here are found hundreds of windmill pumping plants, irrigating from 1 to 15 acres, the pumps lifting from 3 to 14½ quarts per stroke to a height of from 10 to 45 feet. Here are found the large steel mills, with the latest improvements, running day and night whenever

[1] The Windmill as a Prime Motor, by Alfred R. Wolff, 1890, chapter 3, contains an account of the early history of windmills.

the wind velocity is sufficiently great. These reasons induced the writer to select this locality as the field of his investigations.

WELLS NEAR GARDEN, KANSAS.

A brief description of the water supply and the wells of this locality may assist in conveying an understanding of what follows. The water is found in sand and gravel at distances below the surface varying from 8 to 40 feet. This material is in layers of variable thickness and different degrees of coarseness, ranging from fine sand to large gravel. It is overlain by a layer of sandy clay, which in some places will stand vertical for years without any support. In other places there is very little clay in this layer. The wells are usually 3 to 4 feet square, and cased with wood through the top sandy clay to the water-bearing sand; then a wood or galvanized-iron casing from 12 inches to 3 feet in diameter extends down from 8 to 20 feet into the sand to a layer of gravel. Where this latter casing is large, three or more galvanized-iron pipes 6 to 12 inches in diameter are put down in the bottom of it, and these sometimes have wire gauze over their tops to keep down the sand. These galvanized-iron pipes have perforations about one-fourth inch in diameter for a distance of 2 feet or more from the bottom for letting in the water. In many cases instead of this small open well the supply pipe is on a well point whose diameter is the same as that of the supply pipe, and whose length varies with the diameter. These well points have not given satisfaction, and are being replaced by the open well.

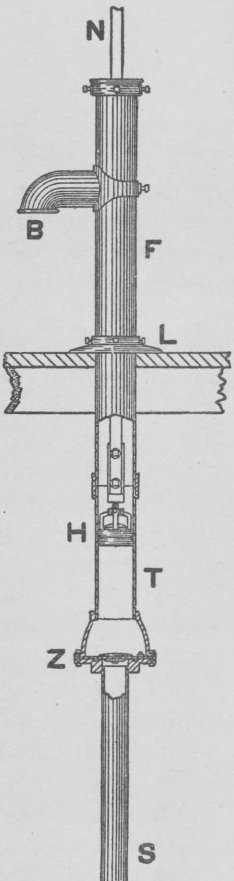


FIG. 1.—View of Gause pump. N, plunger; B, spout; F, discharge pipe; L, flange for platform; H, plunger; T, cylinder; Z, enlarged valve opening and check valve; S, suction pipe.

The difficulty with many of the wells is that they are not large enough; the water in them is lowered too rapidly, producing such a rapid inflow as to carry sand, which cuts the valves and cylinder lining.

PUMPS.

Nearly all the pumps in use in this vicinity with windmills are of the reciprocating-piston type. Fig. 6 shows what is called the Stone pump, manufactured by R. G. Stone, of Garden. They are made in three sizes—6-inch, 8-inch, and 10-inch, these dimensions being the approximate diameter of the discharge pipe. The diameter of the cylinder is less than this by twice the thickness of the brass lining. The valves shown in fig. 7 are of the latest form;

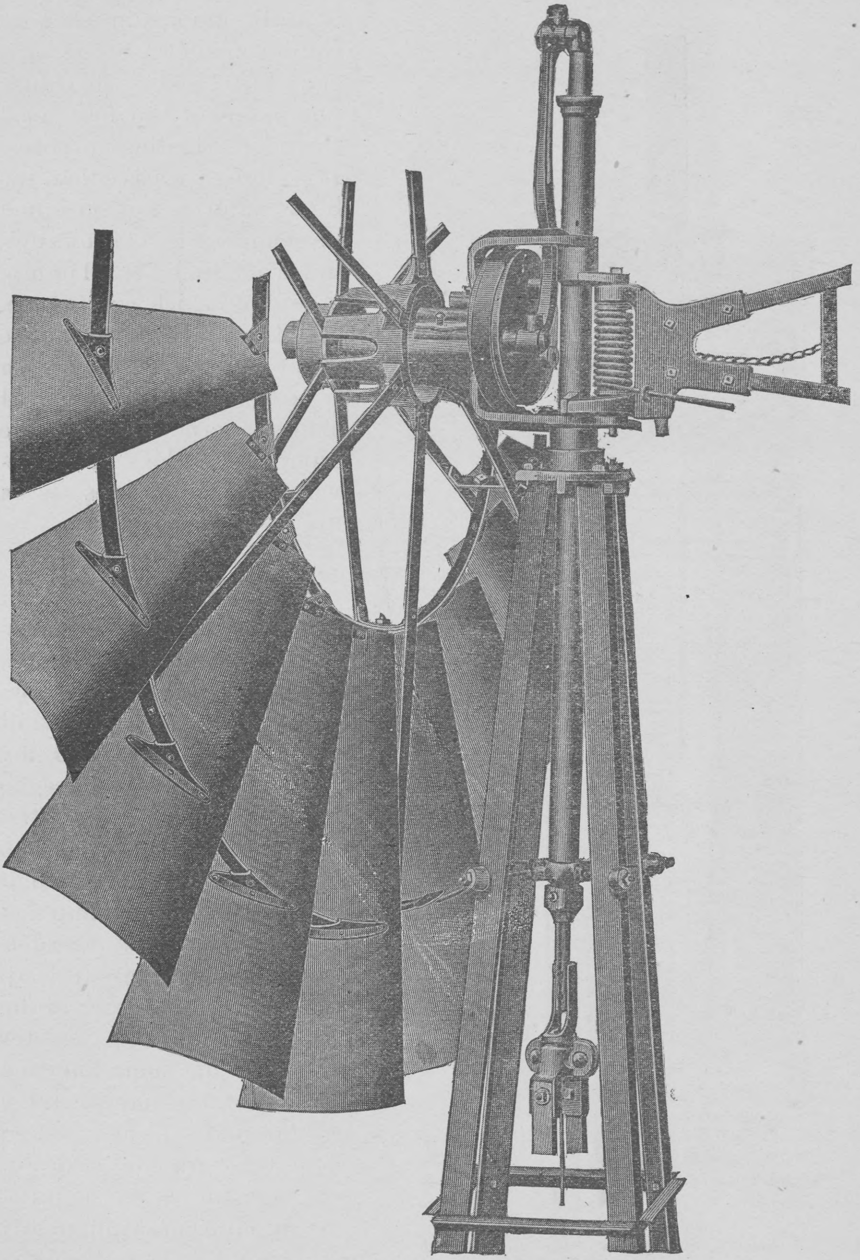


FIG. 2.—Working parts of Woodmanse Mogul.

the plunger valve is of the single-flap or clack form, and the check of the disk form, made so the water can pass up in the center as well as around the sides. In an earlier form of this pump the plunger valve is of the double-flap or butterfly form, and the check of the lift form, but having no opening at the center. Probably nine-tenths of all the pumps in use near Garden are of the Stone variety. Fig. 1 shows the Gause pump, one of the first used there for irrigating purposes. It is more expensive than the Stone, and is not so much used now. Fig. 14 shows cylinder of 8-inch Frizell pump, a few of which are in use. Fig. 4 shows the Woodmanse pump, which is used with windmill No. 2. Fig. 24 shows a crude home-made pump called the "water-elevator." One of these is in use in Garden.

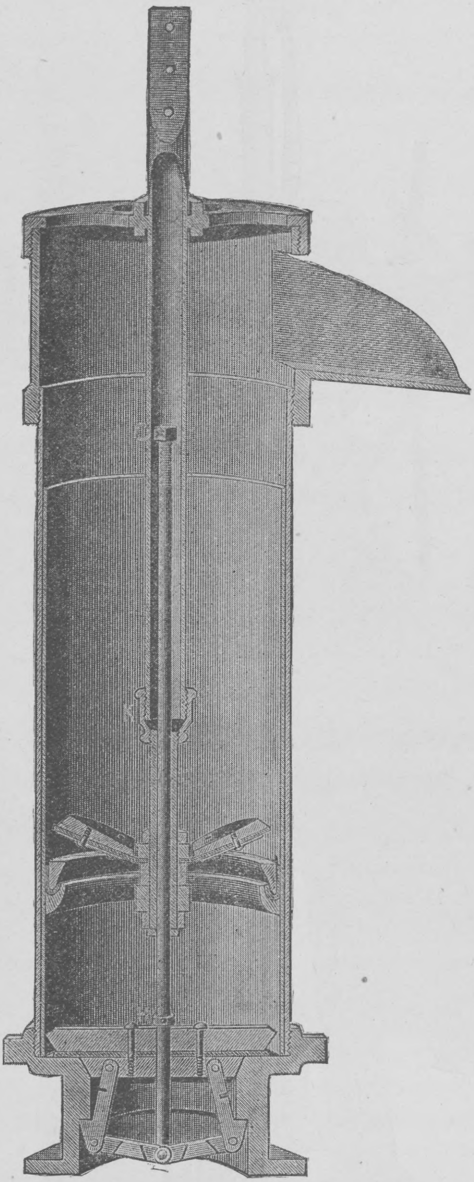


FIG. 3.—Sectional view of Woodmanse pump.

INSTRUMENTS AND METHODS.

The wind velocity was measured with a United States Weather Bureau cup anemometer. Each mile of wind was recorded electrically by one pen of a two-pen register. By means of a little device fastened to the pump an electric circuit is closed at each stroke of the pump and a record made by a recorder. Another electric circuit leading from the recorder to the other pen of the register is closed at each hundred strokes of the pump, and a record made on the register; hence the graphic record of the register shows the number of miles of wind in any given time, and also the number of hundred strokes of pump in the same time.

The anemometer was held on a pole at the height of the axis of the wheel of the windmill. The pole was made so that its length could be increased at will from 25 to 50 feet. The anemometer on the pole is shown in Pls. I and VIII.

The discharge per stroke of the pump was found by catching the water for several strokes in a tub and measuring this with a quart measure. This was found to vary with the number of strokes per minute in a few cases on account of the valves leaking. The discharge given where it varied is for nearly a maximum speed of pump. The lift or distance from the surface of water in the well to the center of the water column as it leaves the discharge pipe was measured when the pump was working quite rapidly. For pump on well points it was estimated from the depth to water when the point was put down, making an allowance for the pumping down of the water.

In the following pages descriptions are given of each of the mills tested, these being illustrated by a few photographs of the mills and surroundings and by drawings of the common form of pumps employed. The descriptions are also accompanied by diagrams showing graphically the results obtained by the measurement of the velocity of the wind and by counting the number of strokes of the pump. These diagrams exhibit at a glance the facts which otherwise can be comprehended only by a careful study and analysis of the figures. As the wind increases from a gentle breeze the pumps run faster, the number of strokes per mile of wind increasing rapidly up to a certain point, but beyond this point the diagrams show that although the wind increases in speed, the pump begins to run slower. This apparent eccentricity is due to the simple fact that nearly all mills are so constructed that for safety they begin to turn out of the wind when it reaches a certain force, and thus decrease their revolutions, until in a heavy wind the movement becomes quite slow or may even cease altogether, the vanes being as a rule turned edgewise to the direction of the air currents.

In these diagrams (figs. 4, 8, 9, 10, 11, 13, 15, 16, 18, and 20) the relation between the movement of the wind in miles per hour and the number of strokes of the pump is shown by the curved line. The space from left to right on these diagrams is proportional to the velocity of the wind, while the distance from the lower line upward is proportional to the number of strokes of the pump. The data expressed by these diagrams were obtained directly from the record given by the anemometer register. The pen of this connected with the anemometer makes, we will assume, 3 short marks (3 miles) in 15 minutes, indicating a mile in 5 minutes, or at a rate of 12 miles an hour. At the same time the other pen, connected with the pump and registering each hundred strokes, makes, say, 2 short marks, showing that the pump has made 200 strokes for this 3 miles of wind movement, or 67 strokes in each mile. This fact is entered upon the diagram by placing a small circle at a distance from the right corresponding to 12 miles per hour and a distance from the bottom corresponding to 67 strokes. In this way each observation is indicated. When these points have been plotted, the smooth curve is sketched so as to occupy an intermediate position among these. In order to determine the number of strokes more accurately than was done by the automatic recorder, these were actually counted for a considerable number of the observations.

DESCRIPTION OF MILLS TESTED.

Mill No. 1.—The tests on this mill were preliminary or experimental toward the perfection of the instruments employed, and were not completed for discussion.

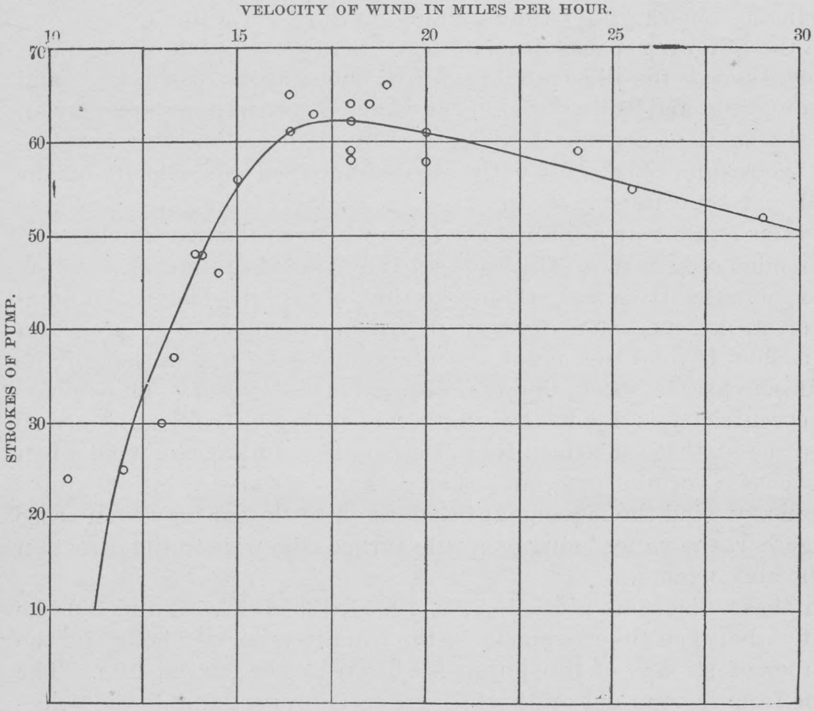
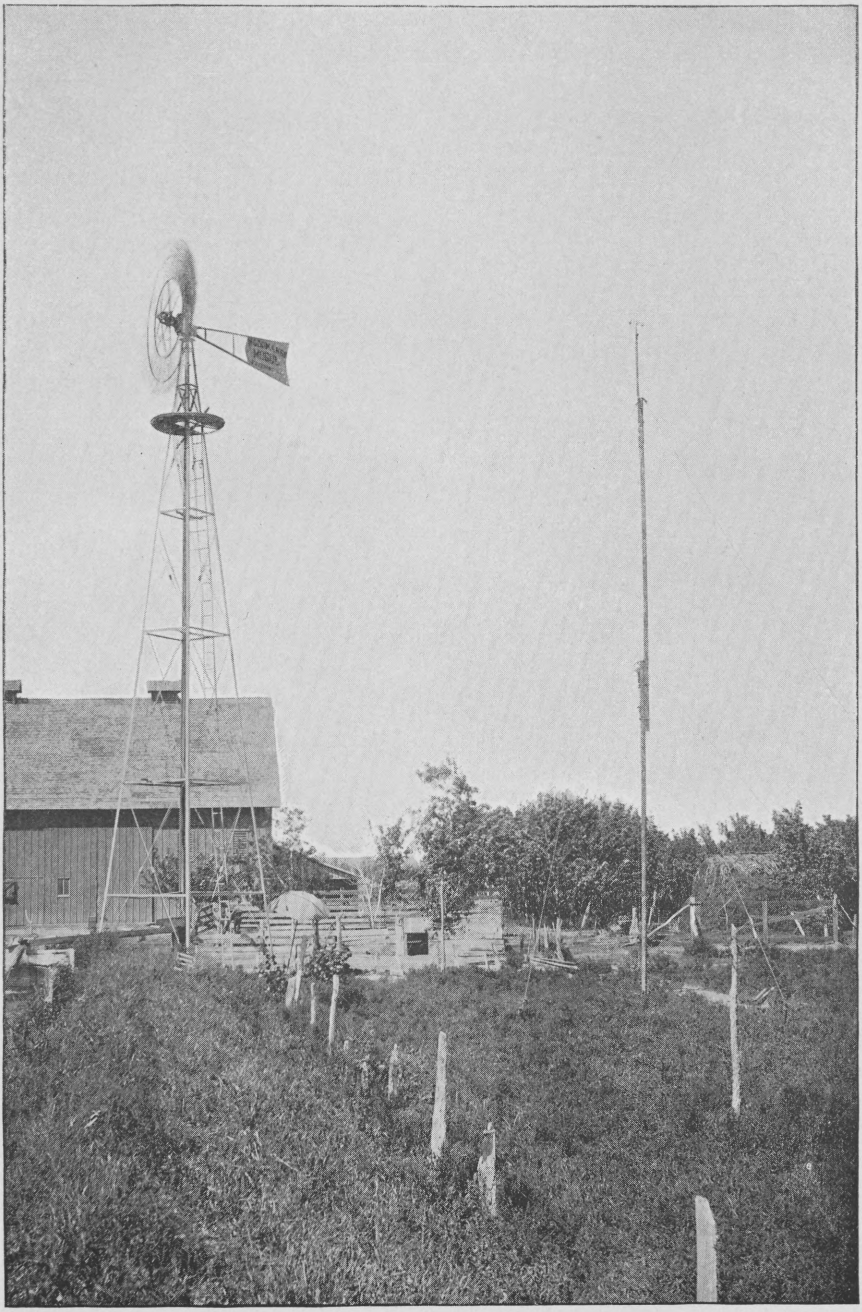


FIG. 4.—Diagram showing results with mill No. 2.

Mill No. 2.—This is a 12-foot Woodmanse Mogul, manufactured by Woodmanse-Hewitt Manufacturing Company, Freeport, Illinois. Pl. I shows the mill, tower, pump, and pond, and fig. 2 the working parts. The tower is steel, 50 feet high to the axis of the wheel. The wind exposure is not good from the north, the mill being 115 feet south of a large barn. The wheel has 30 curved fans, each 36 by 13 by $5\frac{1}{2}$ inches, set at an angle of 30° with the plane of the wheel. It is back geared 3 to 1 and held in the wind by a spring. The pump is Woodmanse make, shown in fig. 3. The cylinder is $9\frac{1}{2}$ inches in diameter; the supply pipe is $5\frac{5}{8}$ inches in diameter; the length of stroke is 12



VIEW OF MILL NO. 2, WOODMANSE, AND ANEMOMETER.

inches. The well is $3\frac{3}{4}$ by $3\frac{3}{4}$ feet to water, a distance of 14 feet. In the bottom of this is put down a 12-inch galvanized iron pipe 20 feet into water, forming a small open well. The lift at the time of test was $17\frac{3}{4}$ feet and the discharge per stroke $14\frac{1}{2}$ quarts. The mean barometer pressure was 26.98 inches, and the mean temperature 94°. The cost of mill, tower, pump, and well was about $210. The curve,

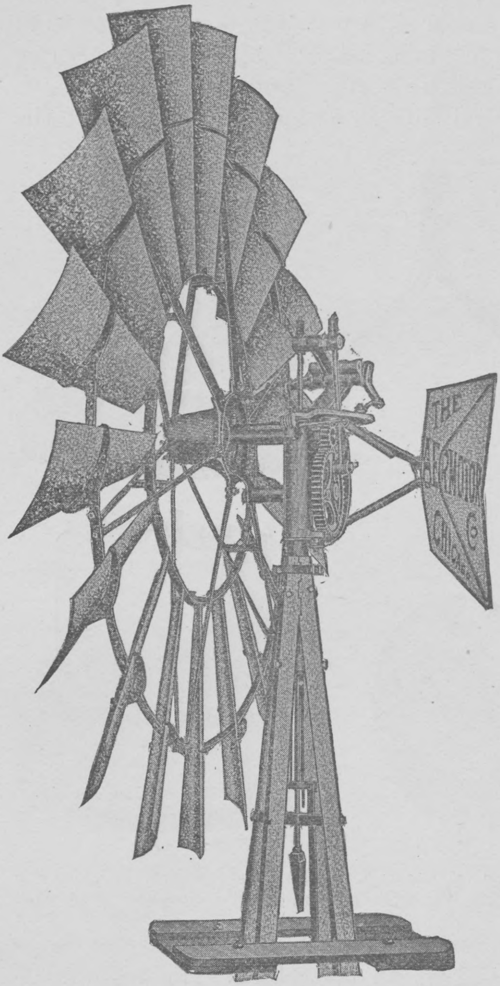


FIG. 5.—Working parts of aermotor.

FIG. 6.—Stone pump.

shown in fig. 4, is for a moderately loaded 12-foot mill (536.2 foot-pounds per stroke), and is seen to start with a wind velocity of about 11 miles per hour. It ascends very rapidly, reaching a maximum at 18 miles per hour, and giving 60 strokes per mile. The rest of the curve to 30 miles has a gentle slope; the number of strokes per minute, from about 5 at 12 miles to about 25 at 30 miles per hour.

Mill No. 3.—This is a 12-foot aermotor, manufactured by the Aermotor Company, Chicago, Illinois. Pl. II shows the mill with its tower, pump, and pond, and fig. 5 the working parts. This mill had been in use about a year and all the parts were in good working order. The tower is made of wood, having the axis of the wheel 30 feet above the ground. The exposure is very good. The wheel has 18 curved fans, each 44 by $18\frac{3}{4}$ by $7\frac{3}{4}$ inches, set at an angle of 31° to the plane of the wheel. It is back geared $3\frac{1}{3}$ to 1, and is held in the wind by a spring. The pump is the Stone make (figs 6 and 7), in which the check valve is of the single-flap variety, and the plunger valve the double-flap variety. The cylinder is $9\frac{1}{2}$ inches in diameter; the

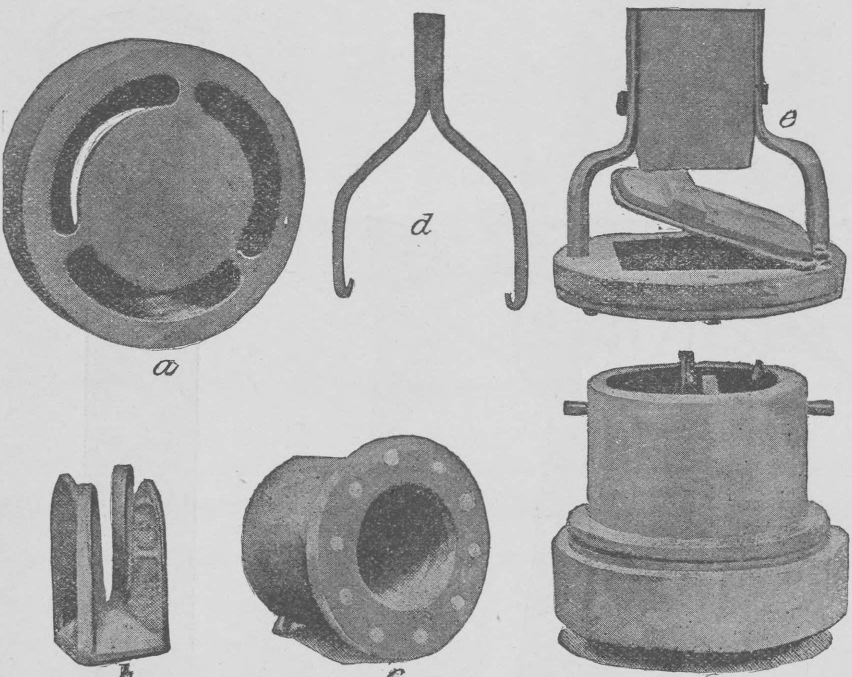
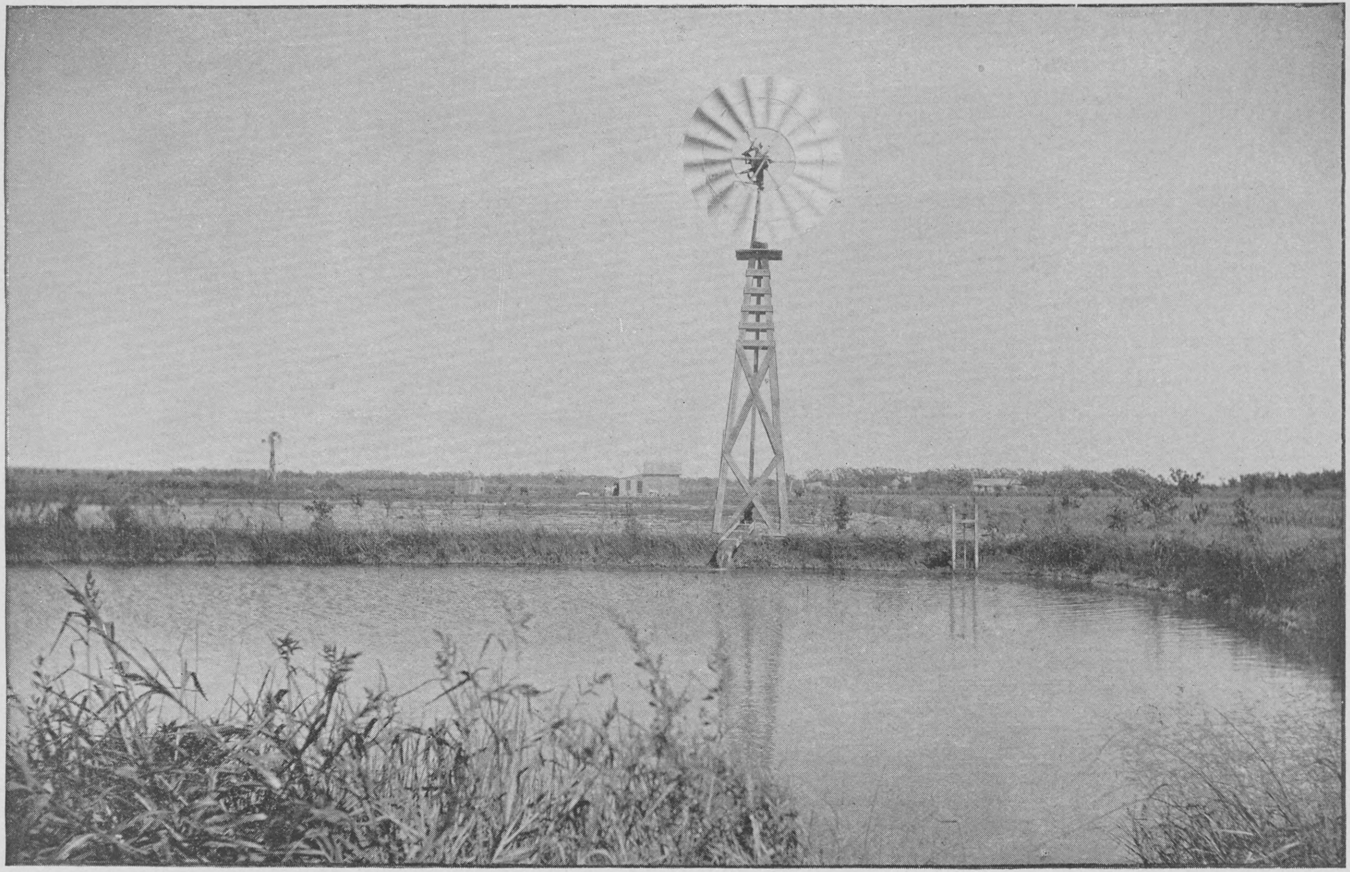


FIG. 7.—Valves of Stone pump. *a*, lower valve-seat; *b*, ring guide to lower valve; *c*, lower or check valve; *d*, hook for removing lower valve; *e*, plunger and valve; *f*=*a*, *b*, and *c* combined.

supply pipe is 4 inches in diameter, and the discharge pipe is 10 inches in outside diameter. The length of stroke is 12 inches and the discharge per stroke $14\frac{1}{2}$ quarts. The well is 4 by 4 feet and is sunk a distance of 8 feet, being down nearly to water. From this to a depth of 18 feet it is 3 feet in diameter. In the bottom of this are three pipes 12 inches in diameter extending down 5 feet farther. The lift at the time of testing was $13\frac{3}{4}$ feet. The barometer pressure was 27.2 inches, and the temperature 85° F. The water is pumped into a pond 80 by 75 feet, and a depth of 22 inches can be drawn off. The cost of the plant, including mill, tower, pump, and pond, was $145.



VIEW OF MILL NO. 3, AERMOTOR.

The curve shown in fig. 8 is for a rather lightly loaded mill—415.3 foot-pounds per stroke. It starts at a velocity of 6 to 7 miles per hour, ascends less rapidly than in fig. 4, attains a maximum at about 15 miles per hour, when the number of strokes per mile is 62, and then descends slowly, reaching 50 strokes at 30 miles. The number of strokes per minute increases from about 5 at 8 miles to 25 at 30 miles.

Mill No. 4.—This, shown in the foreground of Pl. III, is an 8-foot Ideal windmill, manufactured by the Stover Manufacturing Company, Freeport, Illinois. This mill had been in use about one year and all the parts were in good condition. The tower is of wood; the axis of the wheel is 48 feet above the ground. The wheel has 15 fans, each

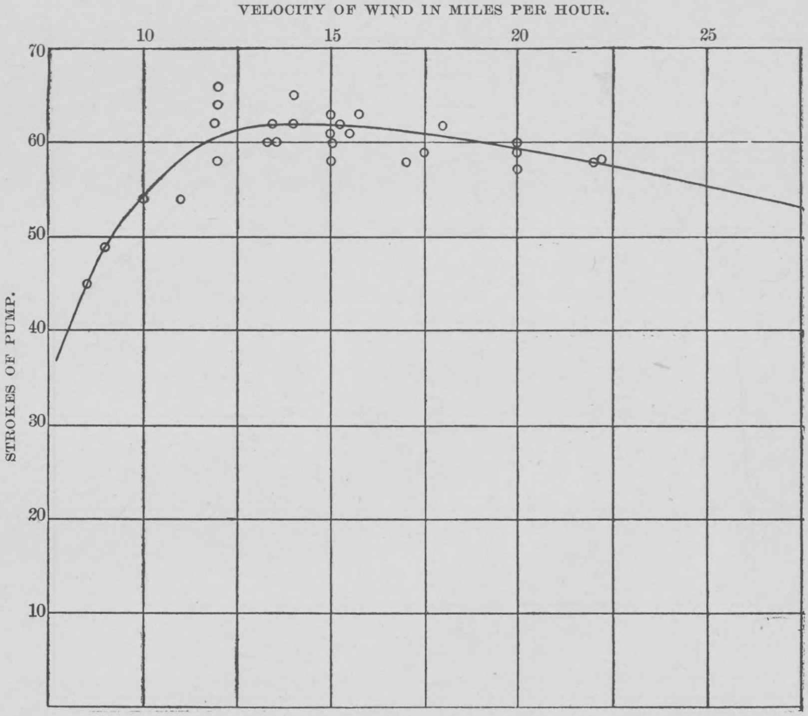


FIG. 8.—Diagram showing results with Mill No. 3.

$16\frac{1}{8}$ by 7 by 30 inches, set at an angle of 29° with the plane of the wheel. It is back geared $2\frac{1}{2}$ to 1 and is held in the wind by a spring. The pump is of the Stone make. The discharge pipe is $5\frac{5}{8}$ inches in diameter and the supply pipe 3 inches in diameter. The length of stroke is 8 inches. The plunger and check valves are of the single-flap variety. The well is $2\frac{3}{4}$ by $2\frac{3}{4}$ feet down, nearly to water, a depth of $5\frac{1}{4}$ feet. The 3-inch supply pipe extends down to a depth of 14 feet, and on the end of it is a 3-inch well point 6 feet long. The lift may vary from $8\frac{1}{2}$ to 20 feet. It was probably about 12 feet at the time of the test. The discharge per stroke was 2 quarts. The mean barometer pressure was 27.19 inches, and the mean temperature 83° F. The water is pumped into a pond 115 by 31 feet and 3 feet deep. The cost of the plant, including mill, pump, well, and pond, was $80.

The curve shown in Fig. 9, although for a quite lightly loaded 8-foot mill—50 foot-pounds per stroke—is seen to start in a 10 to 11 mile wind. The maximum is reached at 19 miles with a speed of 78 strokes. The right portion of the curve is quite steep and is characteristic of this make of mill. Mill No. 18 is the same size and make as this one, and yet with a load of 89.2 foot-pounds it starts in a 7 to 8 mile wind, reaching a maximum at about 13 miles at a speed of 104 strokes per mile. A second test, when the spring that holds the wind wheel

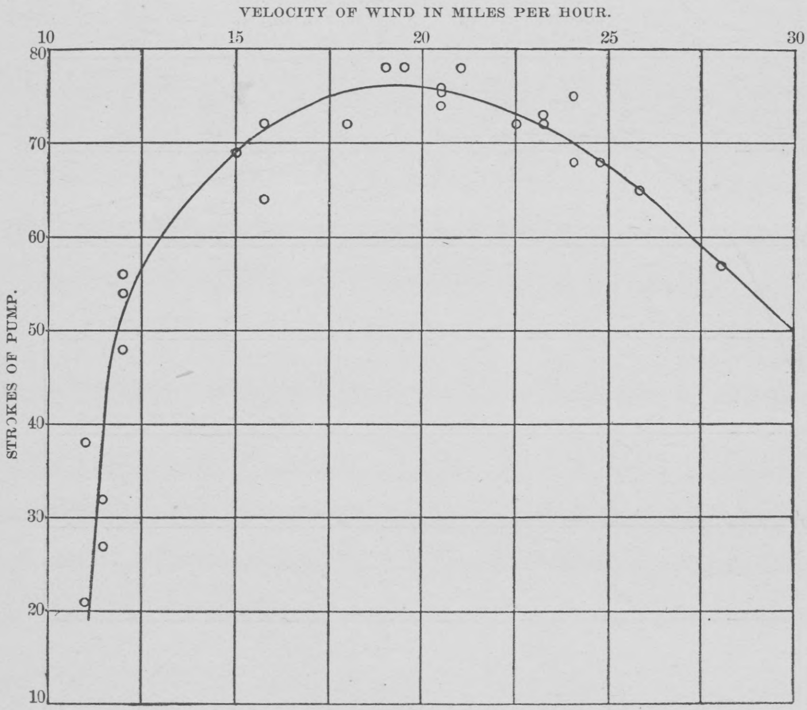
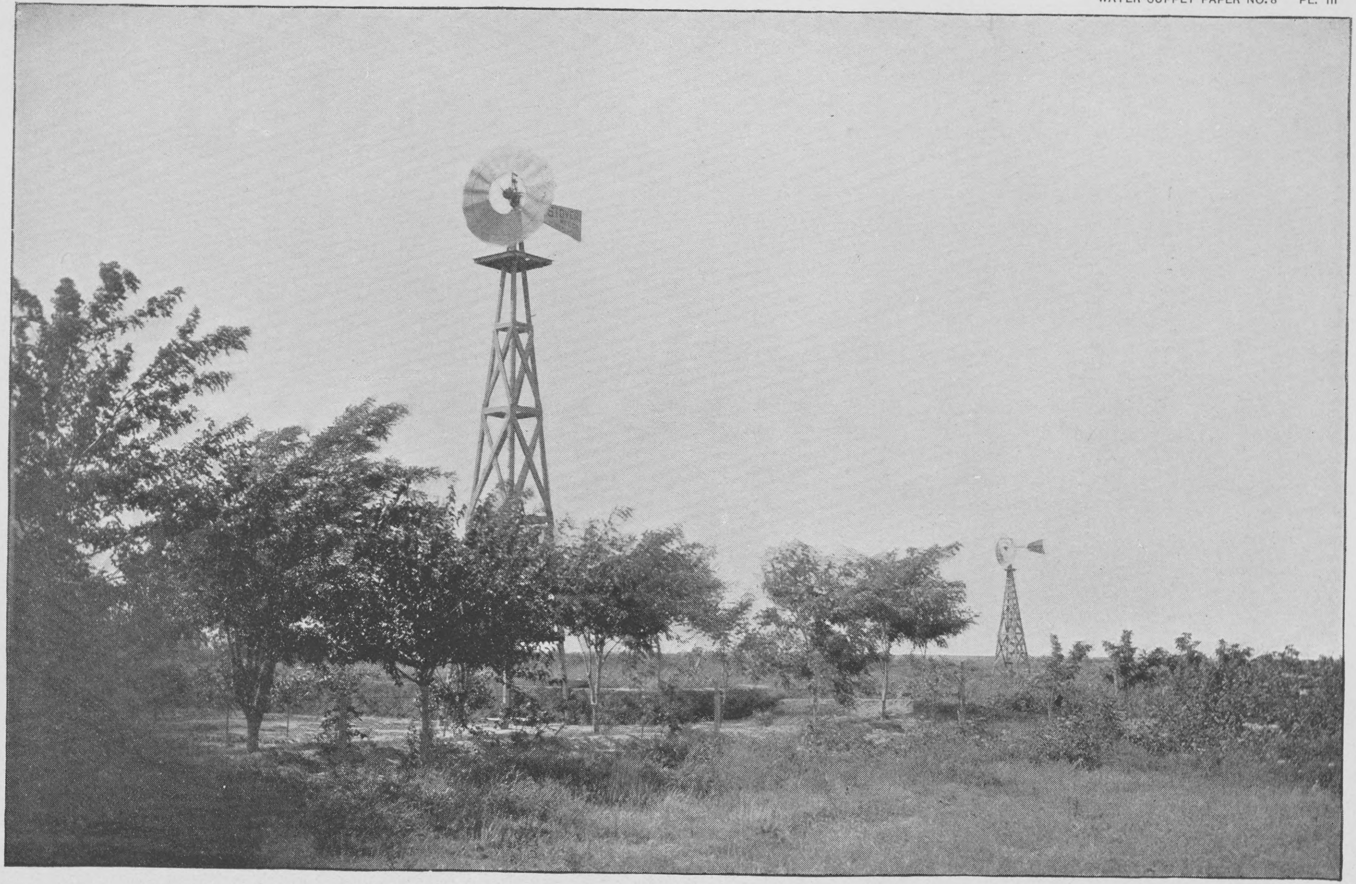


FIG. 9.—Diagram showing results with Mill No. 4.

in the wind was tightened up somewhat, gave the maximum at a velocity of about 15 miles with a pump speed of about 114 strokes. The difference in performance appeared to be due to difference in pumps and wells.

Mill No. 5.—This mill, shown in the background of Pl. III, is an 8-foot aermotor, manufactured by the Aermotor Company, Chicago, Illinois. The tower is of wood and is 28½ feet high to the axis of the wheel. The exposure is good, and all the parts were in good working order at the time of examination, the plant having been in use about one year. The wheel has 18 curved fans, each 30 by 12½ by 5½ inches, making an angle of 29½° with the plane of the wheel. It is



VIEW OF MILL NO. 4, IDEAL, AND NO. 5, AERMOTOR.

back geared $3\frac{1}{3}$ to 1. The pump is Stone make. The discharge pipe is 6 inches in diameter; the supply pipe, 3 inches in diameter. The valves are both of the single-flap variety. The length of stroke is 8 inches. The well is 4 by 4 feet to water, a depth of $10\frac{1}{2}$ feet. A 12-inch wooden curb extends 12 feet farther into the sand and gravel. The discharge per stroke was $3\frac{1}{2}$ quarts and the lift 13 feet. The water is pumped into a pond 110 by 30 by $2\frac{1}{2}$ feet. The cost of plant, including pond, was $80.

This 8-foot mill, with a load of 95 foot-pounds, is shown by fig. 11 to start with an 8 to 9 mile wind, reaching a maximum at 13 to 15 miles with 95 strokes per mile. At 30 miles per hour it is making 77

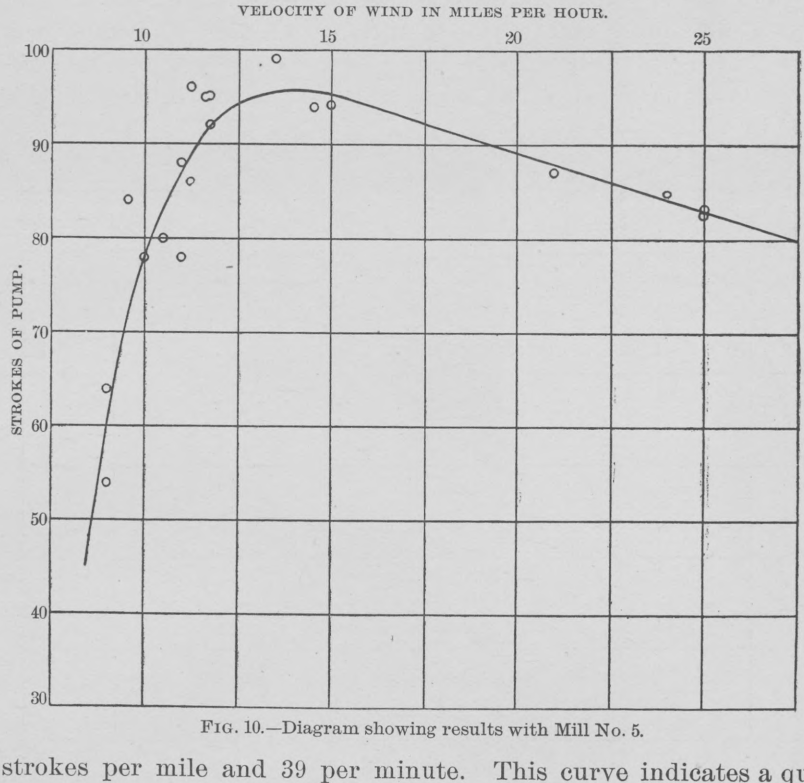


FIG. 10.—Diagram showing results with Mill No. 5.

strokes per mile and 39 per minute. This curve indicates a quite heavily loaded mill.

Mill No. 6.—This mill, shown in the background of Pl. II, is an 8-foot Gem, manufactured by the United States Wind Engine and Pump Company, Kansas City, Missouri. The working parts of the mill are shown in Pl. IV. The exposure is good and all the parts are in good working order, the mill having been in use only about a year. The wheel has 24 curved fans, each $30\frac{1}{2}$ by 10 by $4\frac{1}{2}$ inches, set at an angle of 35° with the plane of the wheel. It is back geared 3 to 1. The wheel is held in the wind by means of a weight. The pump is Stone make. The discharge pipe is 6 inches in diameter, the supply pipe 4 inches in diameter, and the length of stroke 8 inches. The well is open to water for a depth of $6\frac{1}{2}$ feet. The supply pipe is on a well point, the end of which is 16 feet below the surface of the ground. The lift was $9\frac{7}{12}$ feet and the discharge $3\frac{9}{10}$ quarts per stroke. The tower is built of wood and is 24 feet high to the axis of the wheel. The mean barometer pressure was 27.02 inches and the mean temperature 85° F. The plunger valve is of the double-flap variety, and the check of the single-flap variety.

Mill No. 7.—This is a 12-foot aermotor similar to Mill No. 3. The tower is steel, having a height of 31 feet to the axis of the wheel. The exposure was good and all the parts were in good working order, the plant having been in use less than one year. The pump is the Stone make, and is like that with Mill No. 3, except that the check valve is of the solid-lift variety. The lift was $15\frac{1}{2}$ feet, and the discharge $14\frac{3}{10}$ quarts per stroke. The water is pumped into a pond 135 by 50 by $2\frac{1}{2}$ feet.

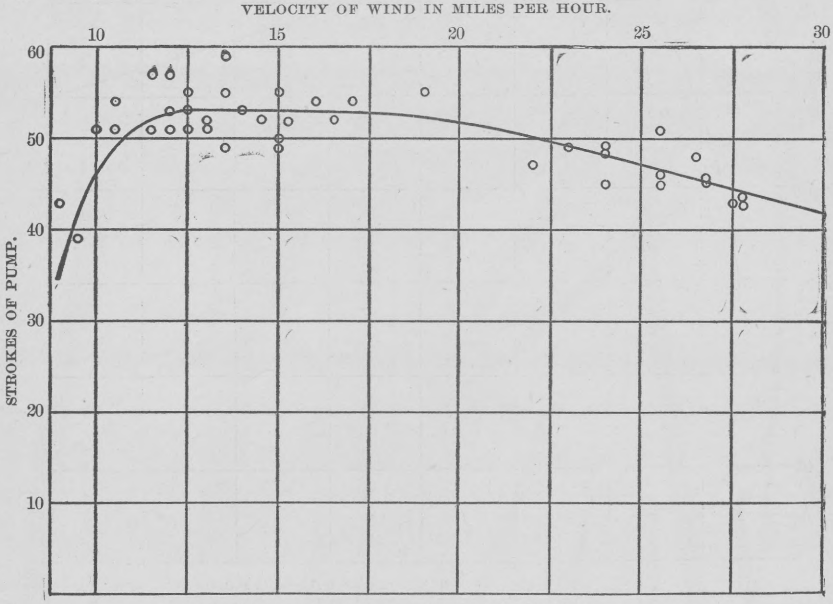
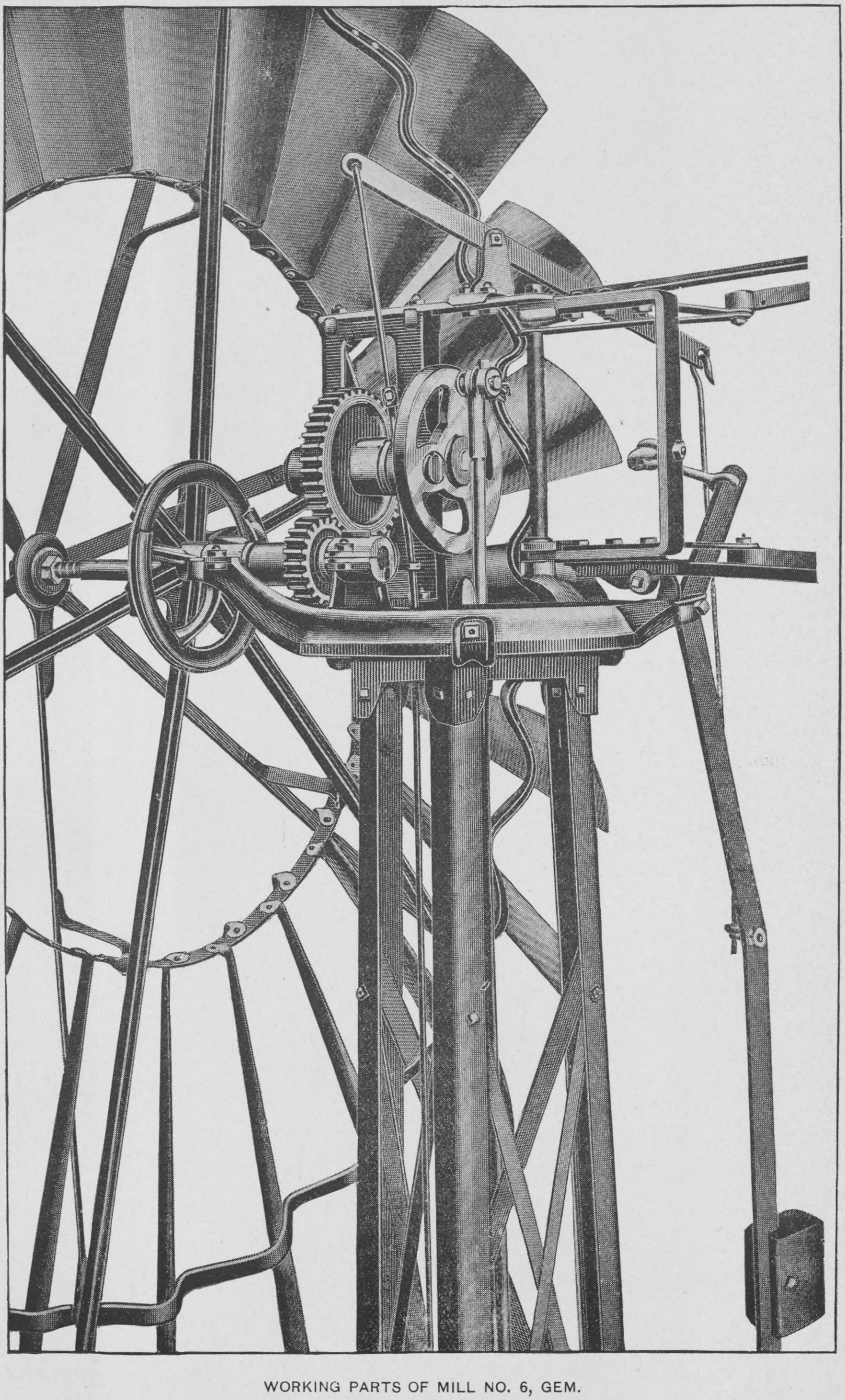


FIG. 11.—Diagram showing results with Mill No. 9, aermotor.

Mill No. 8.—This is a 10-foot Star wooden mill, manufactured by Bradley, Wheeler & Co., Kansas City, Missouri. The tower is made of wood and the axis of the wheel is $35\frac{1}{2}$ feet above the ground. The water is pumped into an elevated tank 20 feet above the surface of the ground, and is used for irrigation. The wheel has 60 plain fans, each 37 by 5 by $2\frac{3}{4}$ inches, set at an angle of 33° to the plane of wheel. It is held in the wind by means of a weight. It is not back geared, a stroke of the pump being made to each revolution of the wheel. The supply pipe is 2 inches in diameter and terminates in a well point, the end of which is 18 feet below the surface of the ground. The cylinder



WORKING PARTS OF MILL NO. 6, GEM.

is 3 inches in diameter, the discharge pipe $1\frac{1}{4}$ inches in diameter, the length of stroke 5 inches. The lift may vary between $28\frac{1}{2}$ and 37 feet. It was estimated to be about 30 feet at the time of measurement.

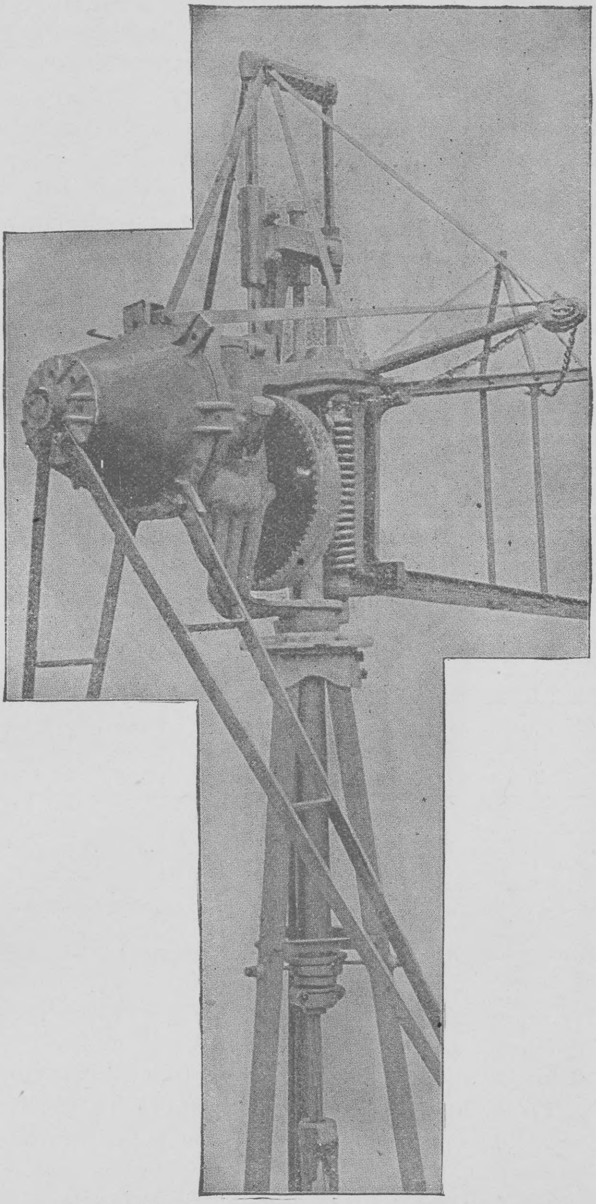


FIG. 12.—Working parts of Mill No. 10, Ideal.

The discharge per stroke was 0.24 quart. The cylinder leaked some at the time of test. After a new cylinder was put in the discharge per stroke was increased to 0.40 quart. The mean barometer pressure was 27.04 inches; mean temperature, 78° F.

Mill No. 9.—This is a 16-foot aermotor. The tower is steel and the axis of the wheel is 30 feet above the ground. The wheel has 18 curved fans, each 59 by 25¾ by 10½ inches, set at an angle of 30° with the plane of the wheel. It is back geared 3⅓ to 1. The discharge pipe is 12 inches in diameter, the supply pipe 6 inches in diameter, the cylinder 8 inches in diameter; the stroke, 16 inches. The well is 4 by 6 feet to a depth of 23 feet, 2 by 2 feet down 8 feet farther, and 18 inches diameter down 14 feet farther. The water is 39½ feet below the surface of the ground. The lift is 44¼ feet and the discharge 11 quarts per stroke. The check valve is of the single-flap variety and the plunger of the double-flap variety. The mean barometer pressure

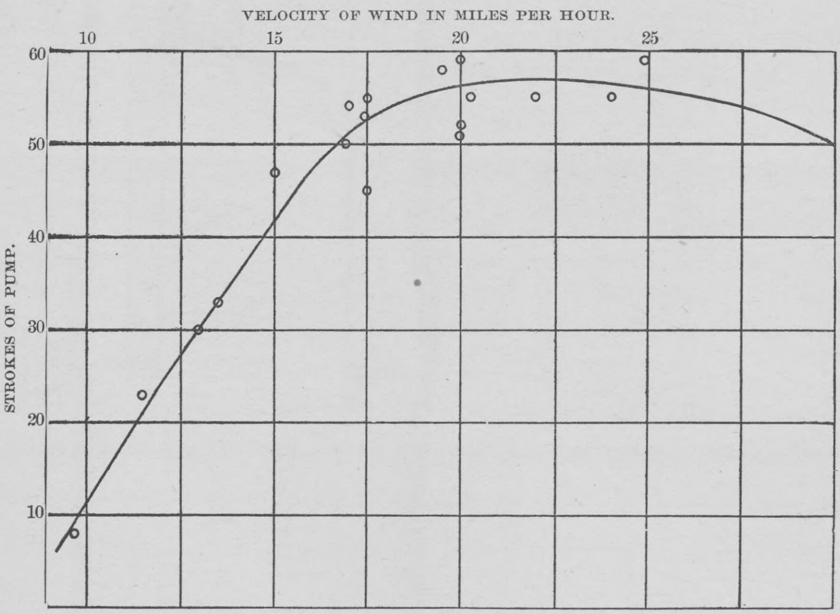


FIG. 13.—Diagram showing results with Mill No. 11, Ideal.

was 27.04 and the mean temperature 93°. This plant has been in use about three years.

The curve, shown in fig. 11, starts with a wind velocity of 8 to 9 miles and reaches a maximum at 13 miles, with a speed of 53 strokes per mile. From this to a velocity of about 19 miles the curve is nearly horizontal. From this point it descends slowly to 32 miles, where it is making 38 strokes per mile. The piston speed increases from the rate of 11 strokes at 12 miles to the rate of 21 strokes at 30 miles per hour.

Mill No. 10.—This is an 8-foot Ideal. The tower is made of wood, the axis of the wheel being 30 feet above the ground. The wheel has 15 curved fans, each 31 by 19 by 7 inches, set at an angle of 29½° with the plane of the wheel. It is back geared 2½ to 1. The supply pipe is $1\frac{1}{2}$ inches in diameter, the cylinder $2\frac{1}{2}$ inches in diameter. The pump is of the common hand kind, with lift valve of the flap form and plunger of the lift variety. The valves leak some, as the discharge is greater when the pump is working rapidly than when it is working slowly. The supply pipe is on a well point 2 feet long and $1\frac{1}{2}$ inches in diameter, whose lower end is 50 feet below the surface of the ground. The lift was 33 feet and the discharge per stroke one-third of a quart when pumping quite rapidly. The mean barometer pressure was 26.94 inches and the mean temperature 97°.

Mill No. 11.—This is a 12-foot Ideal, the working parts of which are shown in fig. 12. The tower is made of steel, the axis of the wheel being 30 feet above the ground. The exposure is good and all the parts are in good working order. The wheel has 21 curved fans, 31 by 19 by 7 inches, set at an angle of $29\frac{1}{2}$° to the plane of the wheel. It is back geared $2\frac{1}{2}$ to 1, and the wheel is held in the wind by a spring. The discharge pipe is 8 inches in diameter and the stroke 12 inches. The supply pipe consists of two 3-inch pipes 14 feet long, each terminating in a 3-inch well point 3 feet long. The valves are both of the single-flap variety. The water is $39\frac{1}{2}$ feet below the surface of the ground. The lift, as nearly as could be ascertained, was 45 feet at the time of measurement; the discharge, 9 quarts per stroke. The water is pumped into a pond 60 by 40 by 6 feet. This plant has been in use about three years. The mean barometer pressure was 26.91 inches, and the mean temperature 91° F.

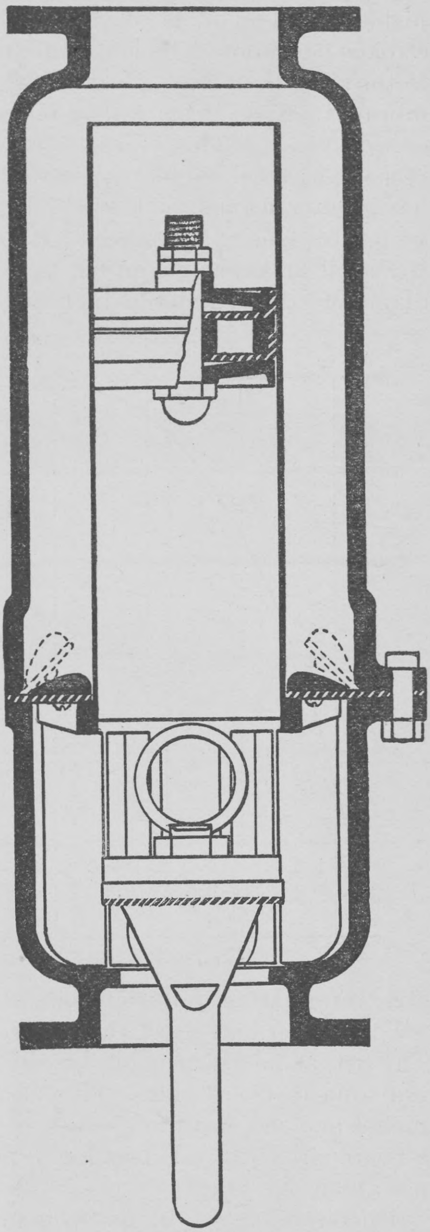


FIG. 14.—Working parts of Frizell cylinder.

This curve, shown in fig. 13, is for a heavily loaded (843.7 foot-pounds per stroke) 12-foot mill. It starts with a velocity of about 10 miles per hour and reaches a maximum at about 23 miles, with a piston speed of 57 strokes per mile. At 30 miles it is making 51 strokes per mile. The maximum point of this curve is much farther to the right than that of any other curve. The number of strokes per minute increases from 5 at 12 miles to 25 at 30 miles.

Mill No. 12.—This is a 14-foot Ideal, shown in fig. 16. The tower is made of steel, 30 feet high to the axis of the wheel. The wheel has 24 curved fans, each $48\frac{3}{4}$ by $17\frac{1}{2}$ by 8 inches, set at an angle of 30° with the plane of the wheel. It is back geared $2\frac{1}{2}$ to 1. The pump is Frizell make, shown in fig. 14. The discharge pipe is 10 inches in diameter; the cylinder $9\frac{1}{2}$ inches; the supply pipe is 6 inches in diam-

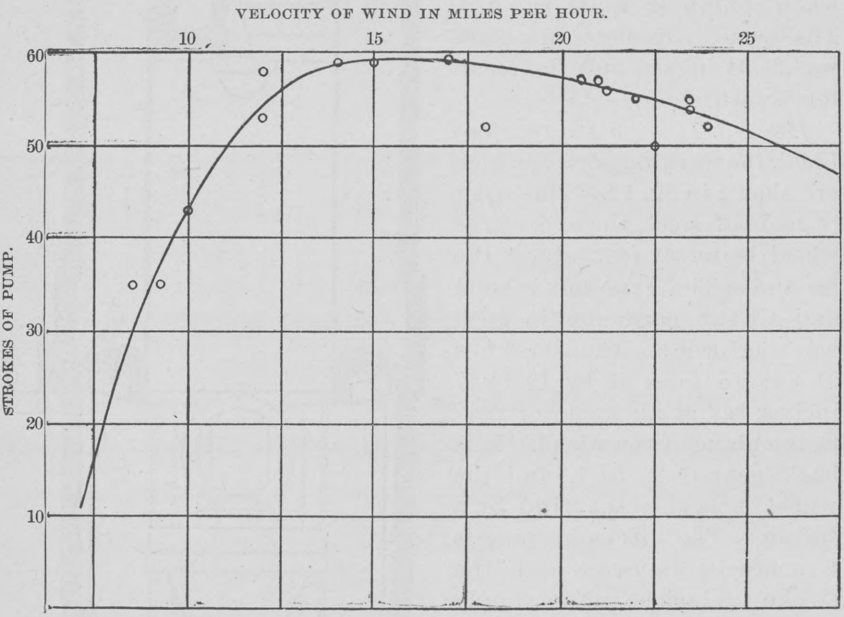


FIG. 15.—Diagram showing results with Mill No. 12.

eter, terminating in a well point 10 feet long and 6 inches in diameter, the lower end of which is 32 feet below the surface of the ground. The lift, as nearly as could be estimated, was 11 feet; the discharge, 11.6 quarts per stroke. The mean barometer pressure was 27.04 inches and the mean temperature 81° F. The water is pumped into a reservoir 100 by 100 feet and 3 feet deep. The pump has been in use about one year.

The curve, shown in fig. 15, is for a very lightly loaded (263.5 foot-pounds) 14-foot mill. This load is only 31 per cent of that of the 12-foot mill, No. 11. The curve starts with a 7 to 8 mile wind and reaches a maximum at 15 miles with a piston speed of 58 strokes per mile of wind. At 30 the piston speed is 47 strokes.

VIEW OF MILL NO. 12, IDEAL.

Mill No. 13.—This is a 12-foot aermotor, shown in Pl. VI. The tower is made of wood, with the axis of the wheel 25 feet above the ground. The exposure is good and the plant in excellent condition, having been in use about one year. The wheel is the same as in mill No. 3. The pump is Stone make; the discharge pipe is 10 inches in diameter; the supply pipe is 5 inches in diameter on a well point 10 feet long, the lower end of which is 17 feet below the surface of the ground. The length of stroke is 12 inches. The plunger valve is of the double-flap type and the check valve of the single-flap variety. The discharge per stroke at the time of the test was 14.4 quarts and the lift about 11 feet. The mean barometer pressure was 27.09 inches and the mean temperature was 91° F. The important difference

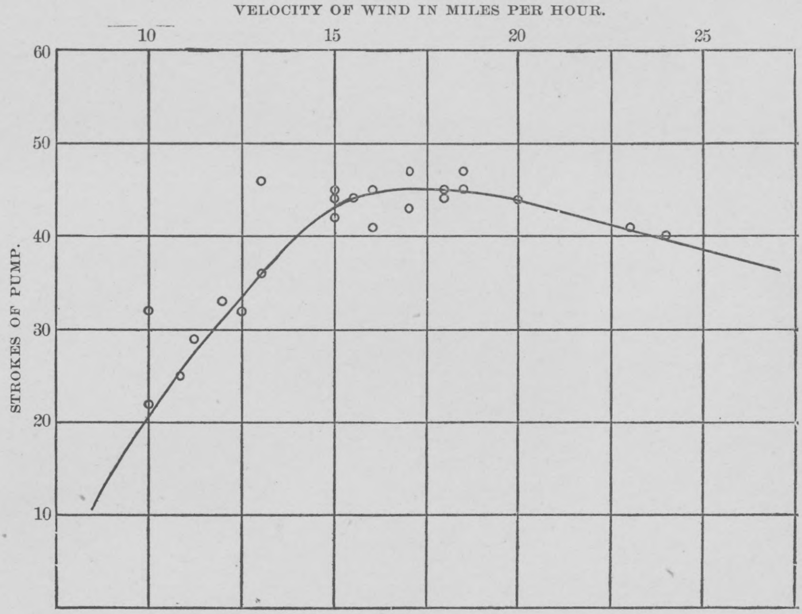


FIG. 16.—Diagram of results with Mill No. 19.

between this plant and No. 3 is that the latter has a 4-inch supply pipe and an open well, while the former has a 5-inch supply pipe on a well point.

Mill No. 14.—This is a 12-foot Gem, like the one shown in Pl. IV, on a 60-foot steel tower. The pump is Gause make; the cylinder is 8 inches in diameter; the length of stroke 9 inches. The supply pipe is a 12-inch open well. The discharge per stroke was $9\frac{3}{4}$ quarts and the lift $15\frac{1}{2}$ feet. The wind velocity was not measured for this mill.

Mill No. 15.—This is a 10-foot Gem, similar to that shown in Pl. IV. The tower is made of wood, the axis of the wheel being 34 feet above the ground. The mill is in good working order, but the exposure is not good on account of trees. The wheel has 24 fans, each 36 by 11 by $4\frac{3}{4}$ inches, set at an angle of 35° with the plane of the wheel. It is back geared 3 to 1. The pump is Stone make; the discharge pipe is 8 inches in diameter, the supply pipe 3 inches in diameter, the stroke 8 inches. The supply pipe is on a 3-inch well point 8 feet long, whose lower end is $21\frac{1}{2}$ feet below the surface of the ground. The plunger valve is of the single-flap form and has a check lift. Depth of water is 10 feet. The discharge per stroke is 7 quarts; the lift, about 15 feet; the mean barometer pressure was 27.05 inches and the mean temperature was 84° F.

Mill No. 16.—This is a 10-foot Halliday, pumping water into the same pond as No. 15. It is similar to the mill shown in fig. 12. The tower is wood, and the axis of the wheel 28 feet above ground. The wheel has 78 fans, each $36\frac{1}{4}$ by 4 by $2\frac{1}{4}$ inches, set at an angle of $35\frac{1}{2}$° to the plane of the wheel. It is not back geared. The pump is Gause

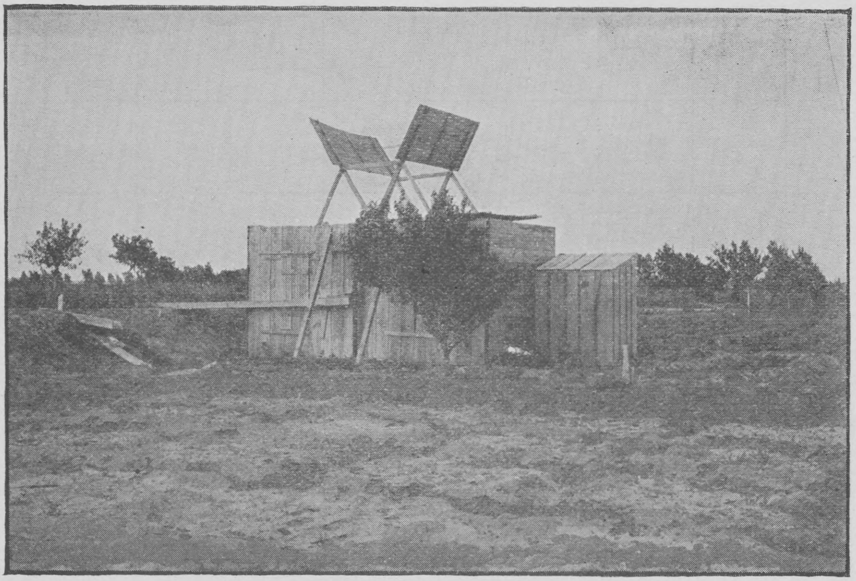


FIG. 17.—View of Mill No. 20, Jumbo.

make, with a discharge pipe 6 inches in diameter; the supply pipe is 4 inches in diameter. There is a 6-inch galvanized iron pipe forming an open well extending 15 feet into the water. The depth to water is 11 feet, the lift is 16 feet, and the discharge per stroke is 3 quarts. The mean barometer pressure was 27.02 inches, and the mean temperature 94° F.

Mill No. 17.—This is a 12-foot improved Gem on a 30-foot steel tower. The wheel has 32 curved fans, each 42 by $11\frac{1}{2}$ by $4\frac{3}{4}$ inches, set at an angle of 37° with the plane of the wheel. It is back geared 2 to 1. The pump is Gause patent, with an 8-inch discharge pipe, 4-inch supply pipe, 12-inch stroke, and an open well formed of a 12-inch wooden casing. The depth to water is $17\frac{1}{4}$ feet, the lift $21\frac{3}{4}$ feet,

VIEW OF MILL NO. 13, AERMOTOR.

and the discharge per stroke $8\frac{3}{4}$ quarts. The mean barometer pressure was 27.05 inches, and the mean temperature 93° F. This mill, although nearly new, does not work well. It is out of plumb. Only a few measurements of the number of strokes per mile of wind were made.

Mill No. 18.—This is an 8-foot Ideal on a 36-foot wooden tower. The exposure was good, and the parts were in good working order. The wheel is like that of Mill No. 4. The pump is Stone make, with a 6-inch discharge pipe. There is no supply pipe, the cylinder being under water, with $3\frac{1}{2}$ inches opening to it from below. The valves are lift variety for check, and single flap for plunger. The well is open, formed by a 10-inch galvanized pipe in the bottom of a part $4\frac{1}{3}$ feet in diameter and 8 feet deep. It is 11 feet to water. The lift is $14\frac{3}{4}$ feet, and the discharge per stroke 2.92 quarts. The mean barometer pressure was 27.01 inches, and the mean temperature 83° F. The cost of the plant, including pond, was $125.

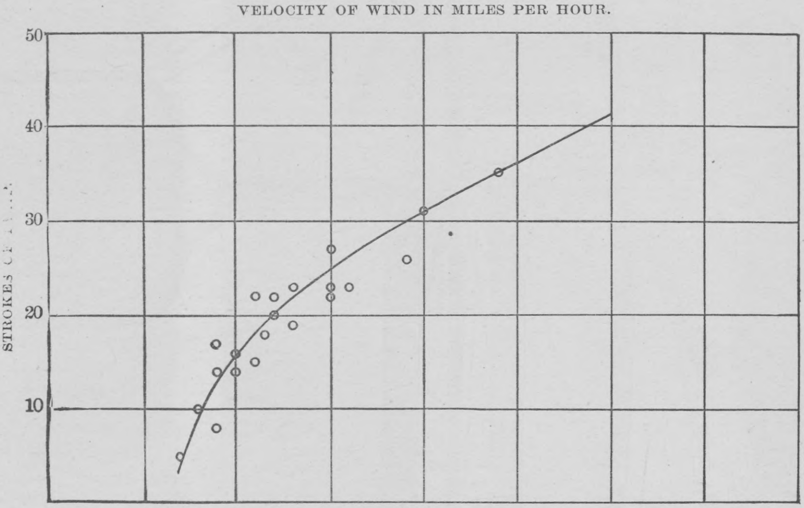
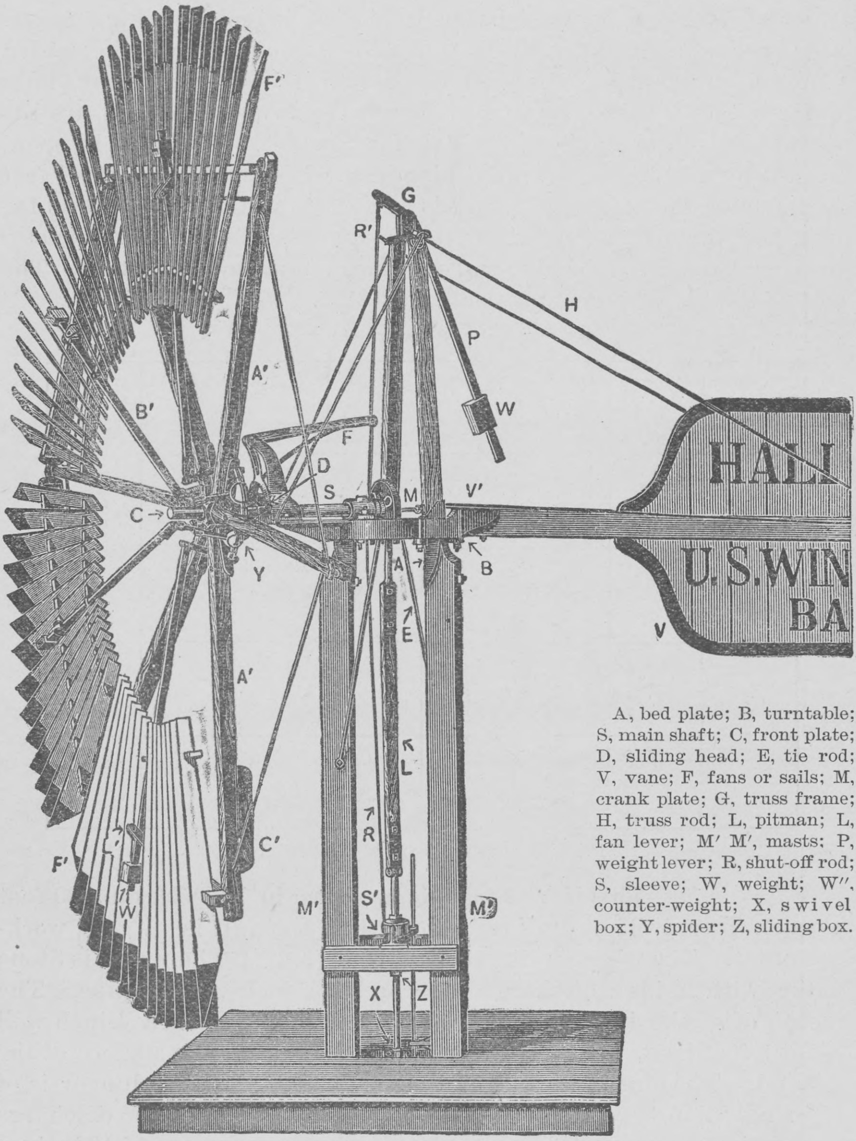


FIG. 18.—Diagram showing results with Mill No. 20.

Mill No. 19.—This is a 12-foot Gem, shown in Pl. VII, on a 30-foot wooden tower. The exposure is good, and the mill is in good working order. The wheel is like that of Mill No. 17. The pump is Stone make, with 10-inch discharge pipe and a 4-inch supply pipe. The length of stroke is 10 inches. The supply pipe is on a 4-inch well point 9 feet long, the end of which is 23 feet below the surface of the ground. The check valve is of the lift type, and the plunger is of the single-flap type. The lift was about 18 feet, and the discharge per stroke 12 quarts. The mean barometer pressure was 27.13 inches, and the mean temperature was 70° F. The water is pumped into a reservoir 120 feet by 60 feet.

The curve, seen in fig. 16, shows that a 9-mile wind is necessary to start this mill, and that the greatest number of strokes per mile of wind is 45, about 25 per cent less than most 12-foot steel back-geared mills. The piston speed is less than for other 12-foot mills, being at the rate of 6 at 12 miles and at the rate of 16 at 25 miles per hour.

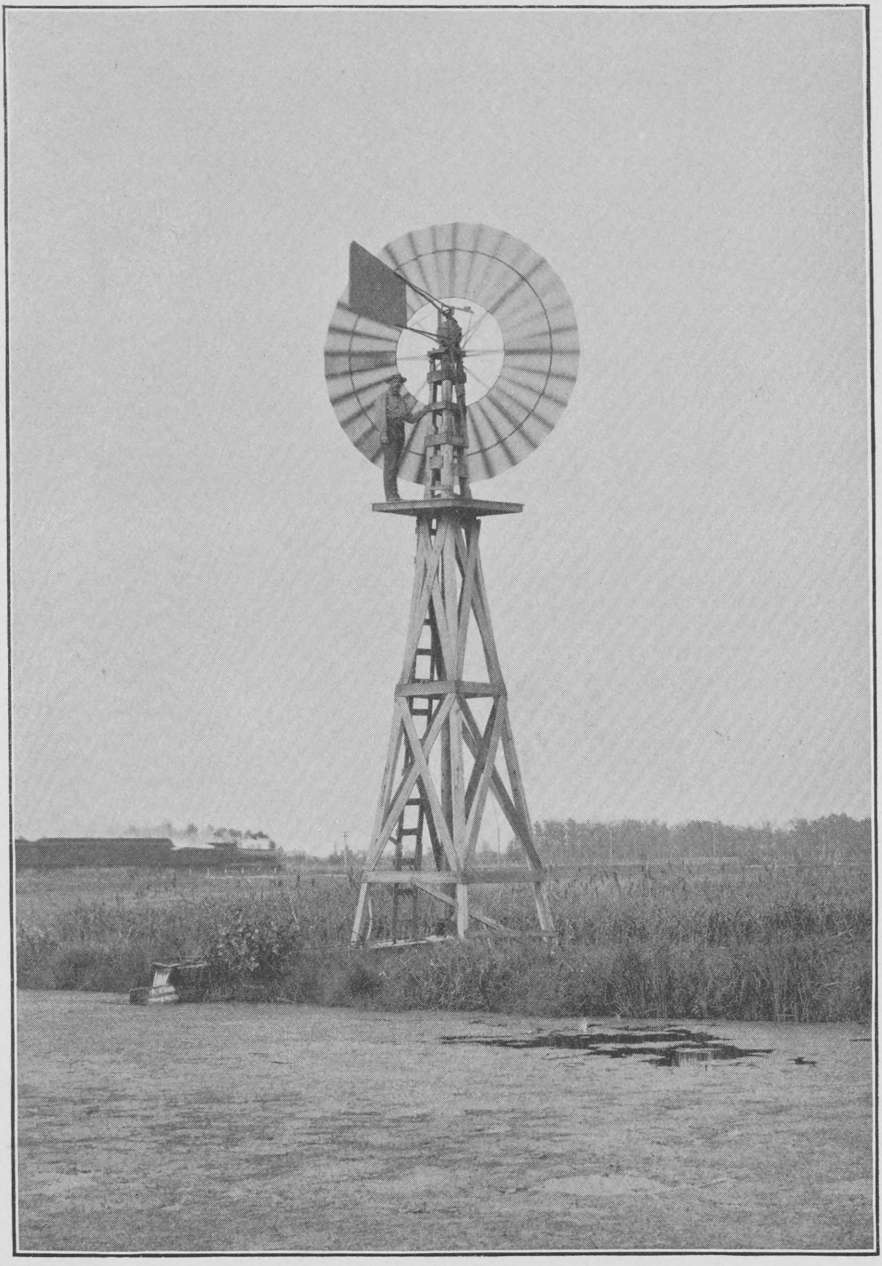
Mill No. 20.—This is a $15\frac{1}{2}$-foot Jumbo, shown in fig. 17. Its axis



A, bed plate; B, turntable; S, main shaft; C, front plate; D, sliding head; E, tie rod; V, vane; F, fans or sails; M, crank plate; G, truss frame; H, truss rod; L, pitman; L, fan lever; M′ M′, masts; P, weight lever; R, shut-off rod; S, sleeve; W, weight; W″, counter-weight; X, swivel box; Y, spider; Z, sliding box.

FIG. 19.—Working parts of Halliday mill.

is a steel shaft 8 feet above the ground. It has 6 fans, each $9\frac{1}{2}$ by $3\frac{1}{2}$ feet; the outer radius is $7\frac{3}{4}$ feet and the inner $4\frac{1}{4}$ feet. This mill operates two pumps, one at each end of the axis, each having a 6-inch



VIEW OF MILL NO. 19, GEM.

cylinder, a 3-inch discharge pipe, and a 3-inch supply pipe on a well point 5 feet long. The discharge of the two pumps was 10 quarts per stroke; the lift was about 14 feet. The mean barometer pressure was 27.09 inches and the mean temperature was 85°. The anemometer was held $14\frac{1}{2}$ feet above the surface of the ground, or at the elevation of the center of a fan when in its highest position. The wheel is set in a large box extending up to a level with the axis of the wheel to prevent the wind from striking the part of the wheel below its axis.

The curve, shown in fig. 18, is seen to be different from the others in that it has no maximum. It starts with a velocity of 13 to 14 miles, and beyond 20 miles it appears to be nearly a straight line.

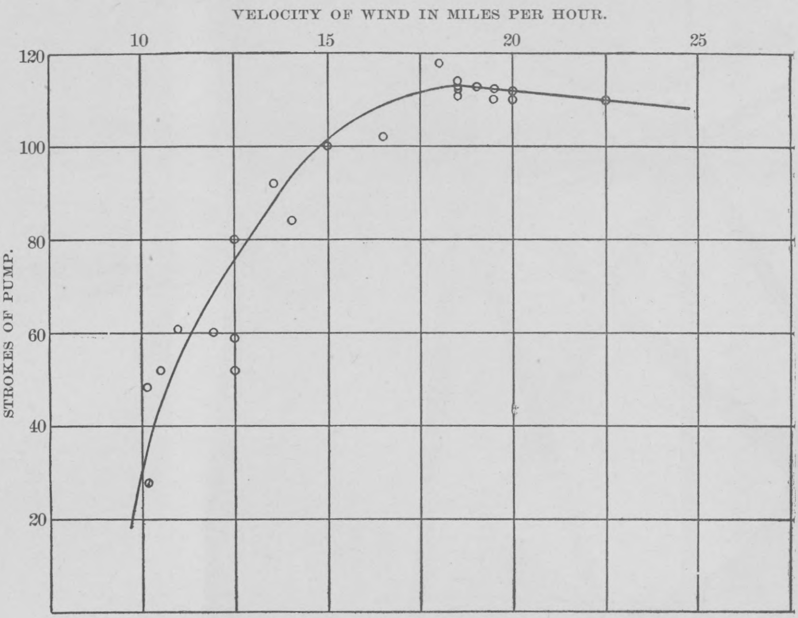


FIG. 20.—Diagram of results with Mill No. 21.

Mill No. 21.—This is a 12-foot Halliday, shown in Pl. VIII, on a 31-foot wooden tower. It was made by the United States Wind Engine and Pump Company, of Batavia, Illinois. The working parts are shown in fig. 19. The wheel has 64 fans, each $42\frac{1}{2}$ by 5 by $2\frac{3}{8}$ inches, set at an angle of 35° with the plane of the wheel. It is not back geared, and regulates itself on the centrifugal principle by the fans taking the direction of the wind. The pump is Stone make, with $7\frac{1}{2}$-inch discharge, 4-inch supply pipe, and 7-inch stroke. The check valve is lift form and the plunger double flap. The well is open, formed by a wooden curb 12 inches in diameter sunk in the bottom of a dug well 9 feet deep. The depth to water was $11\frac{1}{2}$ feet and the lift 15 feet. The discharge per stroke was $4\frac{1}{2}$ quarts when pumping quite rapidly (30 strokes per minute). The valves were not in very good repair, and the pump lost its priming after a time.

This curve, shown in fig. 20, for a lightly loaded (141.5 foot-pounds), direct stroke 12-foot mill, is seen to start with a velocity of 9 to 10 miles, and to reach a maximum at 19 miles, with a piston speed of 112 strokes per mile. At 30 miles the number of strokes is about 98 per mile. The number of strokes per minute varies from 14 at 12 miles to 45 at 25 miles.

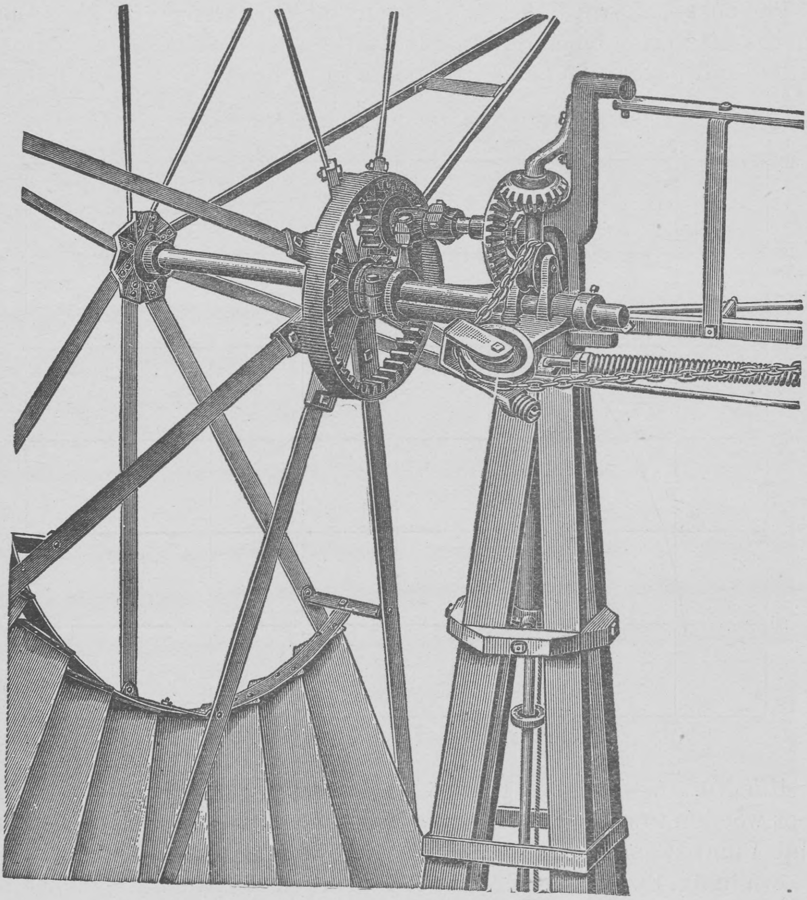
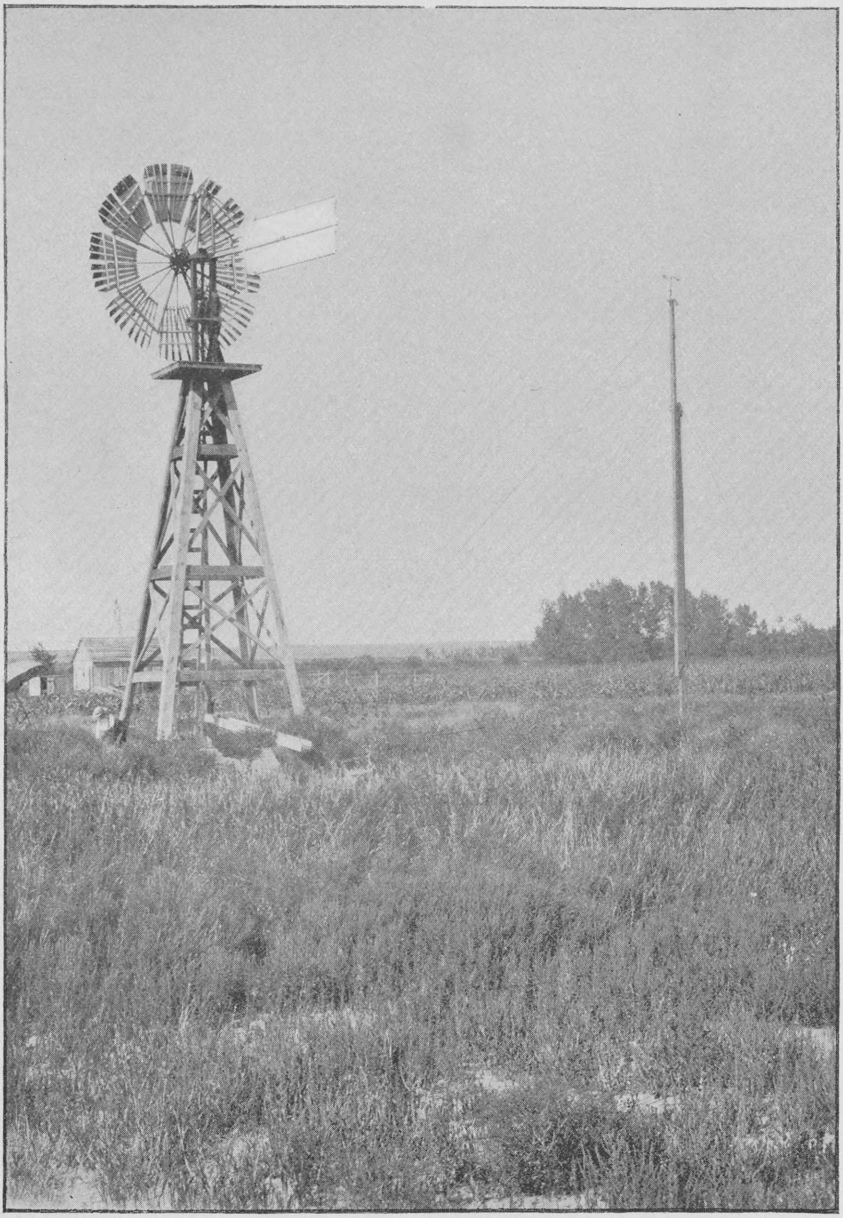


FIG. 21.—Working parts of Power Mill No. 26.

Mills Nos. 22 to 24.—The results obtained from these mills were not sufficiently complete for discussion.

Mill No. 25.—This is an 8-foot steel mill, on a 32-foot steel tower, made by Fairbanks, Morse & Co. The wheel has 18 curved fans, each 29 by $11\frac{3}{8}$ by $5\frac{1}{4}$ inches, set at an angle of 29° with the plane of the wheel. It is back geared $2\frac{1}{2}$ to 1. The pump is of the common hand variety, with $2\frac{1}{2}$-inch cylinder, $1\frac{1}{2}$-inch supply and discharge pipes,



VIEW OF MILL NO. 21, HALLIDAY.

and 4-inch stroke. The well is open $6\frac{1}{4}$ feet to water. The discharge per stroke was 0.31 quart, and the lift $8\frac{1}{2}$ feet. The water raised is used for watering stock.

Mill No. 26.—This is a 14-foot steel power mill, on a 40-foot steel tower, made by the Perkins Windmill Company, Mishawaka, Indiana.

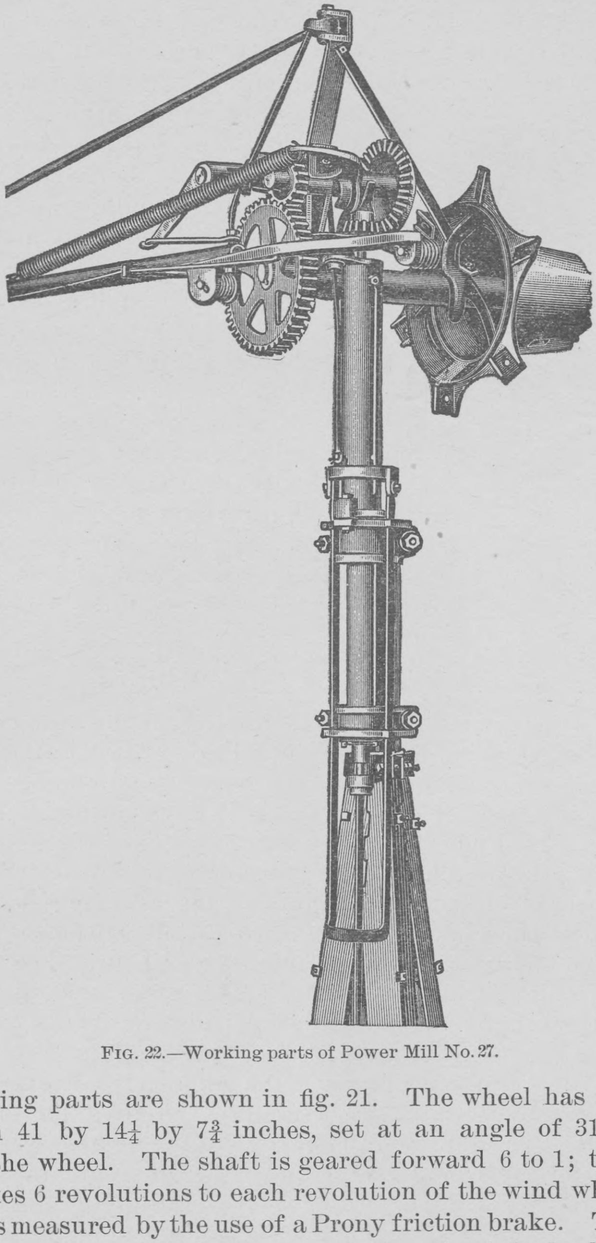


FIG. 22.—Working parts of Power Mill No. 27.

The working parts are shown in fig. 21. The wheel has 32 curved fans, each 41 by $14\frac{1}{4}$ by $7\frac{3}{4}$ inches, set at an angle of 31° with the plane of the wheel. The shaft is geared forward 6 to 1; that is, the shaft makes 6 revolutions to each revolution of the wind wheel. The power was measured by the use of a Prony friction brake. The radius of the brake pulley was 5 inches, and the length of the brake arm $33\frac{1}{2}$

inches. The number of revolutions of the brake pulley per mile of wind was found from a speed counter. This mill was tested twice. Between the dates of testing, some repairs were made to the shafting, causing the cogwheels to bind less tightly. The figures given in Table I for this mill are those obtained from the second test, and are much larger than those from the first test. The load was 6 pounds on the arm 33½ inches long. The mill has been in use about one year.

Mill No. 27.—This is a 12-foot power aermotor on a 30-foot steel tower. The wheel is the same as in mill No. 3. The horizontal shaft is geared forward 6 to 1. Fig. 22 shows the working parts of the mill and fig. 23 the foot gear. A 9½-inch brake pulley was clamped to the horizontal shaft at *a*, fig. 23. The power was measured by a Prony friction brake on this 9½-inch pulley, the arm of the brake being 35¼ inches in length. The number of revolutions per mile of wind was found from a speed counter. The mean barometer pressure on October 10, 1896, when quite a number of measurements of power were made, was 28.9 inches, and the mean temperature was 46° F. These have been taken as a standard, and measurements made on other days reduced to what they would have been had the pressure been at the standard.

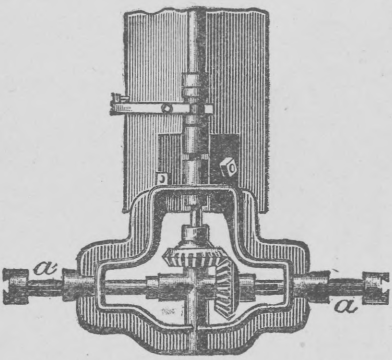


FIG. 23.—Foot gear of power mill No. 27.

DISCUSSION OF THE RESULTS.

The following table gives in condensed form the results obtained from the observations upon the windmills described in the preceding pages. This table shows, first, the arbitrary number given to the mill; next, the name of the mill and that of the owner of the particular one tested. Following this is the diameter of the wind wheel in feet. After this are four general divisions within which the observations have been classified according to the average velocity of the wind in miles per hour, beginning with a wind movement of 8 miles per hour and ending with one of 30 miles per hour. The number of strokes per mile of wind was obtained, as before stated, directly from the record given by the anemometer register. The second set of figures, that giving the number of strokes per minute, is obtained by simple division from the first set, the number of strokes per mile being divided by the number of minutes required for the wind to make a mile. The next set of figures gives the number of gallons per hour that each pump was lifting under the different wind velocities. This is found from the preceding set by multiplying the number of strokes per minute by sixty (number of minutes in an hour), and this by the number of gallons raised at each stroke.

The next set of figures, that giving the useful work in horsepower for the different velocities, is found from the preceding set by multiplying each of these by the factors which convert the number of gallons or the quantity of water raised through the given height into the corresponding horsepower. One horsepower is the rate of work when 33,000 pounds is raised to a height of 1 foot in one minute, or, in other words, is 33,000 foot-pounds. Thus to obtain the useful work in horsepower it is necessary to multiply the number of gallons by the weight in pounds of each gallon and by the height in feet to which this is raised, and to divide this by 33,000. This is expressed mathematically by the simple formula: Horsepower $= \frac{n\, q\, g\, h}{33,000}$, where n is the number of strokes per minute, q the number of gallons per stroke, g the weight in pounds per gallon, and h the lift in feet.

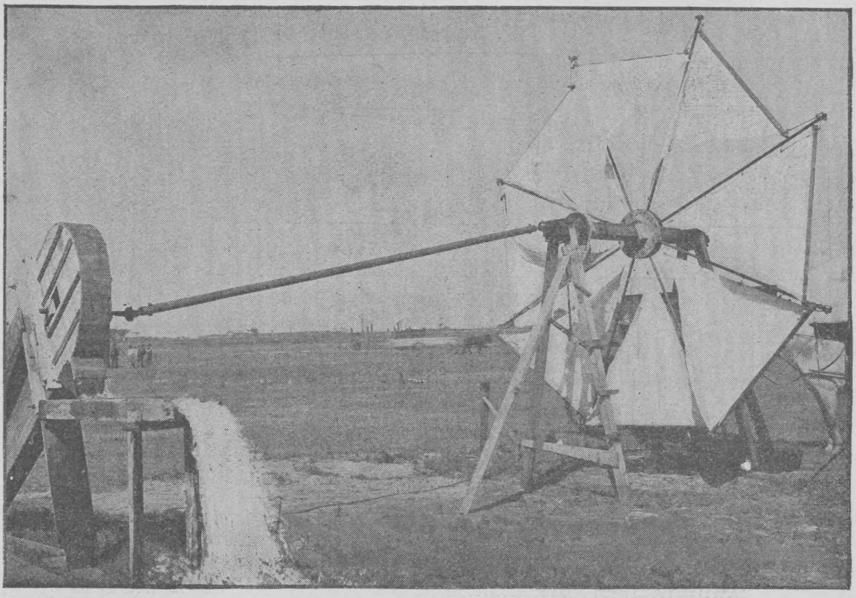


FIG. 24.—View of Defender mill and elevator.

The latter part of the table gives, after useful work in horsepower, the foot-pounds of useful work per stroke of the pump, this being obtained in the manner indicated above by multiplying the amount of water in pounds raised each stroke into the height in feet. Next to this is the total vane area of the mill in square feet, this being obtained by a careful measurement of the size of the vanes. Next to this is appended the total lift in feet, obtained as noted under the descriptions of the mills, and also the size of the pump (inside diameter of the cylinder) and the length of stroke, both of these being given in inches.

Results of measurements and computations of pumping mills.

Mill No.	Name.	Owner.	Size.	Number of strokes per mile of wind when velocity per hour in miles is— 8	12	16	20	25	30	Number of strokes per minute when velocity per hour in miles is— 8	12	16	20	25	30
			Ft.												
2	Woodmanse	I. L. Diesem	12	----	26	60	61	56	51	----	5.2	16.0	20.3	23.3	25.3
3	Aermotor	T. D. Carless	12	40	60	62	60	56	50	5.3	12.0	16.4	19.8	23.1	25.0
4	Ideal	E. S. Austin	8	----	52	73	76	68	50	----	10.2	19.3	25.3	28.1	25.0
5	Aermotor	Ella Horner	8	----	93	94	90	83	77	----	18.6	25.1	29.8	34.6	38.5
6	Gem	W. J. James	8	----	62	67	66	61	58	----	12.4	17.9	22.0	25.4	28.5
7	Aermotor	O. V. Folsom	12	----	57	59	57	53	47	----	11.4	15.8	19.0	22.1	23.5
8	Star	J. C. Kitchen	10	210	150	----	----	----	----	28.0	30.0	----	----	----	----
9	Aermotor	F. M. Dunn	16	----	53	53	52	47	42	----	10.6	14.1	17.2	19.6	21.0
10	Ideal	do	8	106	125	125	----	----	----	14.1	25.0	33.3	----	----	----
11	do	do	12	----	24	48	57	56	50	----	4.8	12.7	18.8	23.3	25.0
12	do	D. M. Frost	14	23	55	59	58	52	----	3.1	10.9	15.7	19.2	21.5	----
13	Aermotor	Wm. Coulters	12	----	55	64	63	59	55	----	11.0	17.1	21.0	24.6	27.5
15	Gem	Jas. Allen	10	----	39	45	44	35	----	----	7.8	11.9	14.7	14.6	----
16	Halliday	do	10	30	113	127	128	126	----	4.0	22.6	33.9	42.7	52.5	----
17	Gem	D. R. Menke	12	----	30	48	52	----	----	----	6.0	12.8	17.3	----	----
18	Ideal	Fred. Pile	8	60	101	*a* 114 98	102 84	79 66	----	8.0	20.2	26.1	28.0	27.5	----
19	Gem	W. E. Trell	12	----	31	45	44	38	----	----	6.2	11.9	14.7	16.0	----
20	Jumbo	W. T. Cowhick	$15\frac{1}{2}$	----	----	20	32	42	----	----	----	5.3	10.7	17.5	----
21	Halliday	J. E. Hunt	12	----	70	107	112	107	----	----	14.0	28.5	37.3	44.6	----
25	Fairbanks	Wm. Brown	8	92	146	140	114	80	----	12.3	29.2	37.3	38.0	33.3	----

Mill No.	Number gallons pumped per hour when wind velocity per hour in miles is— 8	12	16	20	25	30	Useful work in horsepower when wind velocity per hour in miles is— 8	12	16	20	25	30	Foot-pounds useful work per stroke of pump.	Vane area, in square feet.	Lift, feet.	Size of pump. *b*
2	----	1,131	3,480	4,415	5,069	5,503	----	.085	.260	.322	.379	.411	536.2	69.4	17.75	$9\frac{5}{8}$x12
3	1,153	2,610	3,567	4,306	5,014	5,437	.067	.151	.207	.250	.291	.315	415.3	72.9	13.75	$9\frac{1}{2}$x12
4	----	306	579	759	843	750	----	.015	.029	.038	.043	.038	50.0	36.1	12.00	$5\frac{5}{8}$x8
5	----	977	1,318	1,564	1,817	2,021	----	.053	.072	.086	.099	.111	94.9	33.7	13.00	6 x8
6	----	725	1,047	1,287	1,486	1,667	----	.029	.042	.051	.059	.065	77.6	36.9	9.60	$6\frac{1}{8}$x8
7	----	2,445	3,387	4,075	4,740	5,041	----	.160	.221	.266	.309	.329	461.9	72.8	15.50	$9\frac{1}{2}$x12
8	101	108	----	----	----	----	.013	.014	----	----	----	----	15.0	59.8	30.00	3 x5
9	----	1,749	2,326	2,838	3,234	3,465	----	.325	.433	.448	.601	.644	1,013.3	133.6	44.25	8 x16
10	70	125	167	----	----	----	.010	.017	.023	.032	----	----	22.8	42.0	33.00	$2\frac{1}{2}$x6
11	----	648	1,714	2,538	3,150	3,375	----	.123	.325	.481	.600	.639	843.7	75.3	45.00	$7\frac{7}{8}$x12
12	535	1,880	2,708	3,312	3,709	----	.025	.087	.125	.153	.172	----	263.5	103.6	11.00	$9\frac{1}{2}$x12
13	----	2,376	3,694	4,536	5,314	5,940	----	.110	.171	.210	.247	.275	330.0	72.8	11.00	10 x12
15	----	819	1,250	1,543	1,533	----	----	.053	.082	.101	.099	----	219.0	47.3	15.00	8 x8
16	180	1,017	1,526	1,922	2,362	----	.012	.067	.103	.130	.159	----	100.0	61.3	16.00	6 x8
17	----	765	1,632	2,206	----	----	----	.070	*c*.149	.202	----	----	385.0	75.8	21.75	8 x12
18	348	879	1,135	1,218	1,196	----	.022	.054	(082) .070	(092) .076	(088) .074	---- ----	89.2	42.0	14.75	$5\frac{1}{2}$x8
19	----	1,116	2,142	2,646	2,880	----	----	.085	.162	.201	.219	----	450.0	77.6	18.00	10 x10
20	----	----	795	1,605	2,625	----	----	----	.047	.095	.154	----	291.2	73.6	14.00	6 x12
21	----	945	1,924	2,518	3,010	----	----	.060	.121	.159	.184	----	141.5	69.7	15.00	$7\frac{5}{8}$x7
25	57	136	173	177	155	----	.002	.005	.007	.008	.005	----	5.5	30.2	8.50	$2\frac{1}{2}$x4

a Two pumps, each 6 by 12 inches.
b Inside diameter of cylinder by length of stroke.
c Test after increasing the tension of spring which holds wind wheel in the wind.

It is seen that mills of the same size differ very much in the useful work they do, and that some of the large mills are doing very little more work than some of the smaller ones. Nos. 4 and 18 are the same size and make; the wells, however, are very different; the latter is doing two or three times more work than the former. The 12-foot mill, No. 11, is doing nearly as much useful work as the 16-foot mill, No. 9, and three or four times more useful work than the 14-foot mill, No. 12, while it is doing 300 per cent more work than No. 21. The $15\frac{1}{2}$-foot Jumbo will probably do very little more work during the season than a good 8-foot mill.

RELATION BETWEEN WIND VELOCITY AND STROKES.

The preceding diagrams show graphically the relation between the wind velocity in miles per hour and the strokes of the pump. The curves, as will be noted, differ considerably; but with the exception of No. 23 for Mill No. 20, they agree in that they rise rapidly, reaching the highest point or greatest number of strokes at from 13 to 19 miles of wind velocity. From this point they descend slowly. They differ much in the position of the beginning of the curve, or the velocity required to start the mill. Some will run in an 8-mile wind; others require a 10 or 12 mile wind to start them. Some rise less rapidly than others; a notable case is Mill No. 11. Some descend much more rapidly than others after reaching the highest point. This is especially true of the 8-foot Ideals. Mill No. 12 (Pl. V) required a 14-mile wind to start it, and does not appear to have a maximum.

The shape of the curve, especially the position of its beginning point, is due to the load on the pump, or the number of foot-pounds per stroke. Increasing the load moves the curve to the right and raises it higher. This will be shown more fully in the discussion of power Mill No. 27. The height of the highest point and its position depend on the tension of the spring, or the weight which holds the mill in the wind. The greater the tension, the higher the summit and the farther it is to the right. Mill No. 20 has no method of reducing the wind area, and hence the curve has no summit, as shown in fig. 17. The less the tension in the spring, the steeper the descent from the highest point. The gearing—that is, the mechanism for causing the pump to make a stroke to each revolution of the wheel, or only a stroke every second or third revolution—modifies the curve. If working with a direct stroke, the curve is much higher and is farther to the right than if back geared, as shown by a comparison of mills 3 and 21, shown in figs. 8 and 20.

USEFUL WORK IN HORSEPOWER.

The relation between wind velocity and horsepower is shown graphically for five 12-foot mills on diagram No. 31 and for four 8-foot mills on diagram No. 32. Examining the five curves of fig. 25, we see that No. 11, the one which gives the greatest horsepower, has the heaviest load and requires the greatest wind velocity to start it. No. 2 has about five-eighths the load of No. 11, does less work, and requires about the same wind velocity to start the pump. No. 3 has a lighter load than No. 2 and will start in a wind of about 7 miles per hour. No. 19 has a little heavier load than No. 3 and does much less work at all velocities. The latter requires a 9 to 10 mile wind to start it, while the former will start in a 7 to 8 mile wind. No. 21 is doing the least work of the five, and requires about an 11-mile wind to start it. It is a wooden mill working direct stroke, while the others are steel mills and back geared. It must be understood in this comparison that no correction or allowance is made for difference in temperature and barometric pressure, nor for the fact that in Nos. 11 and 19 the pumps are in well points, while in the others they are in open wells.

It is seen that in fig. 25 none of these curves reach a maximum

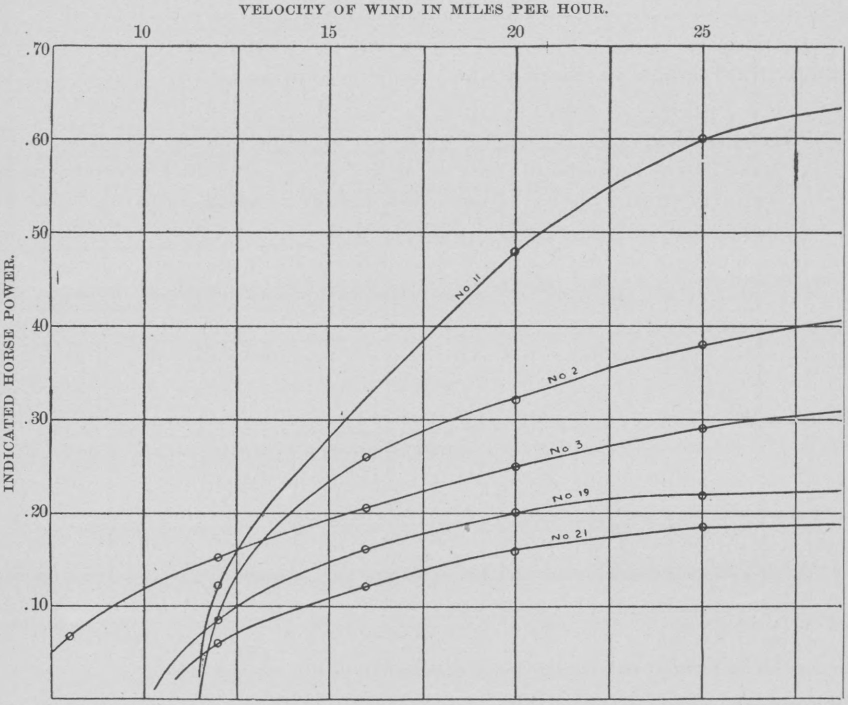


FIG. 25.—Diagram showing relation between horsepower and wind velocity for five 12-foot mills.

point below 30 miles per hour. They do, however, for some higher velocities, since the work per stroke of pump is nearly constant for each pump for all velocities, though not the same for one pump as for another. These curves also give the relation between wind velocity and number of strokes of pump per minute.

In fig. 26 the curve for No. 18 is seen to reach a maximum at 20 miles per hour, and No. 4 reaches a maximum at about 25 miles per hour. The others reach their maximum points for velocities at about 30 miles. These maximum points are points of greatest piston speed, and are produced by a reduction of wind area, the wind wheel turning out of the wind. This make of mill is seen to "govern" or turn out of the wind at a lower velocity than other makes. Comparing the curves on diagram No. 26, we see that the one doing the most work in high velocities is No. 5, the one which is the most heavily loaded. The principal differences between Nos. 4 and 18—the ones giving the most and the least work for velocities less than 22 miles per hour—are in the load and well. No. 4 has five-ninths of the load of No. 18, and is on a well point. The two doing the least work are on well points.

Mill No. 25 is used to pump water for stock. Comparing it with that of, say, No. 5, we see that its load is about five-ninths, and that it is doing about one-tenth as much work as the latter. It will start with a wind velocity of about 6 miles per hour, while the latter requires a velocity of about $8\frac{1}{2}$ miles.

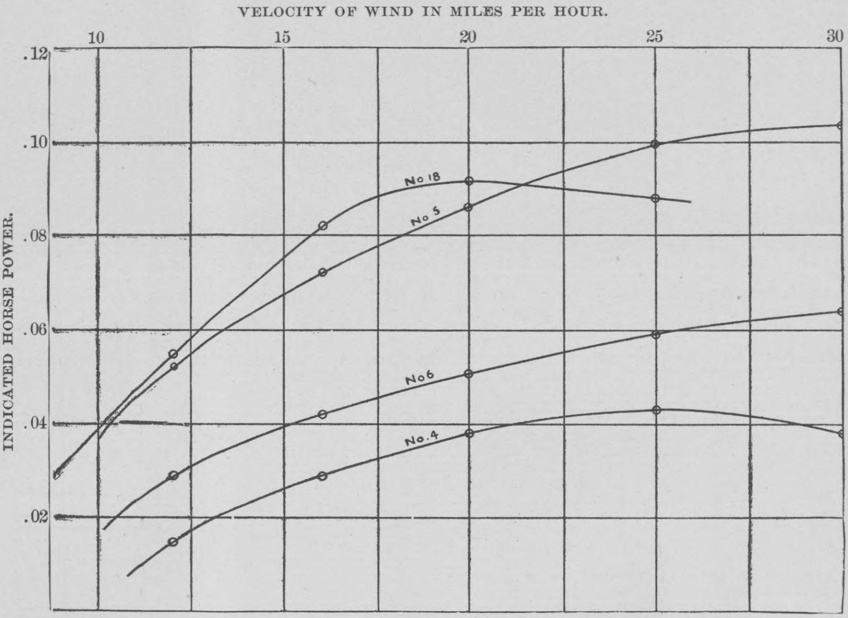


FIG. 26.—Diagram showing relation between horsepower and wind velocity for four 8-foot mills.

COMPARISON OF BACK-GEARED AND DIRECT-STROKE MILLS.

Comparing the curves of fig. 25, which gives the relation between horsepower and wind velocity for five makes of 12-foot mills, we see that the one giving the least power is working direct stroke. It required the greatest velocity to start it, and is doing less work at all velocities than any of the other four. In a 20-mile wind it is making 40 strokes per minute, and in a 25-mile wind 48 strokes per minute. This is too rapid a rate; 30 strokes per minute is as rapid as a pump of this size should work. Hence the horsepower of this mill would be less than shown in the diagram if run at a proper rate. The only way that it can be made to do more work without back gearing it is by increasing the load per stroke, but this will increase the velocity necessary to start it, and cause it to remain idle a greater part of the time. Comparing the working of this mill and, say, No. 3, we see that the work per stroke of No. 3 is 415 foot-pounds and that of No. 21 is 141 foot-pounds, or the former is doing about three times as much work per stroke as the latter, and the latter is making about 1.8 times as many strokes per minute as the former in a wind velocity of 16 or more miles per hour. The former being back geared $3\frac{1}{3}$ to 1, its wheel is revolving about 1.9 times faster than that of the latter. Now, examining the curves of fig. 27, we see that the speed of the wheel has much to do with the useful work done. When the speed is low, as it must be in a mill working direct stroke and not too rapidly for proper action of the valves of the pump, a slight increase in load reduces the speed a good deal. When the speed is nearly doubled, as in the case of Mill No. 3, the load may be increased considerably without reducing the speed much. Hence back gearing not only enables the mill to work with a given load in a much less wind velocity than one working direct stroke with the same load, but it enables the wheel to run at a velocity that gives more power.

PUMP LOAD DUE TO WELL POINT.

On examining well points that have been used for a time, it is seen that many of the little openings through which the water passes into the pump have become filled with fine grains of sand, thus reducing the area through which the water can enter the pump. If this area was of the proper amount when the point was new, it has become too small after having been used for a time, or after standing in the ground for a time without being used. If this area is too small to allow free flow into the pump, an added load is put on the pump.

To measure the mean pull of the pump, an instrument was devised by Mr. R. G. Stone, of Garden, consisting essentially of a spiral spring, whose compression was proportioned to the pull, and a pencil which moved up and down over a smooth surface. The spring was calibrated and the pull in the pump rods of four pumps measured with it. The four pumps selected were operated by the same size and make of mill, and the pumps were the same except as to size of supply pipe, valves, and kind of well. The discharge was practically the same, but the lifts differed slightly. These were Nos. 3, 7, 13, and 22. The following table gives the pull in each case after reducing to a common lift of 17 feet:

Added load due to pump.

No. mill.	Lift.	Kind of well.	Mean pull.
			Pounds.
3	$13\frac{3}{4}$	Open	597
7	17	Open	734
13	12	4-inch well point	944
22	$13\frac{1}{2}$	4-inch well point	819

The straining capacity of No. 7 is not as great as that of No. 3, and the resistance of the valves is greater in No. 7 than in No. 3.

USEFUL WORK DONE IN A GIVEN TIME.

The useful work which two mills of the same wind area, exposure, and general character will do depends on the magnitude of the load on the mill and the wind velocity. If the mill is heavily loaded it will do more work in velocities of 12 or more miles per hour, and less in lower velocities than one of a lighter load. The useful work done in a given time is the product of the work done per hour at the mean velocity, and the number of hours during that time. If the mean velocity at a given place is low, the mill load must be less for maximum work than that at a place where the mean velocity is higher. To illustrate this fact we use the results of tests of two 12-foot pumping mills (fig. 25): No. 11, heavily loaded, and giving the greatest horsepower of all the mills tested at high wind velocities; and No. 3, giving the greatest power at low velocities. The useful work per stroke of pump is 844 foot-pounds for No. 11, and 415 foot-pounds for No. 3. The useless work of the former is greater than that of the latter, since the pump is on two well points in the former, while the pump of the latter is in an open well.

The relation between the horsepower and the wind velocity for these mills is shown in the diagram (fig. 25). The curves are seen to cross each other at a wind velocity of 12½ miles per hour. For less velocities than this No. 3 is doing more work per hour than No. 11, and for greater velocities No. 11 is doing more work than No. 3. If the velocity at this place were, say, not more than 13 miles per hour, it is very evident that mill No. 3 would do more work in any time than No. 11.

There is no record of wind movement at Garden, Kansas, for any considerable length of time. There is one, however, for Dodge, 50 miles east of Garden, kept by the United States Weather Bureau, which may be used for this purpose. The following table gives the mean number of hours per month for the six months, April to September, for the seven years 1889 to 1895, that the wind movement was 0–5, 6–10, 11–15, 16–20, 21–25, 26–30, 31 and upward miles per hour.

Mean wind movement at Dodge, Kansas, for the seven years 1889 to 1895.

Months.	0-5	6-10	11-15	16-20	21-25	26-30	31 and upward.
April	116	175	157	113	76	43	40
May	116	195	168	120	74	39	32
June	120	187	139	111	86	49	28
July	144	218	176	117	57	23	9
August	178	230	152	99	62	18	5
September	166	182	152	93	75	34	18
Mean	140	198	157	109	72	34	22

It is seen from this table that the wind velocity is 5 miles or less per hour for 140 hours per month at this place. During this time neither of these mills will do any work, as neither will start in a 5-mile wind. The velocity is from 6 to 10 miles per hour for 198 hours per month. Mill No. 3 will start in about a 7-mile wind, and hence will run about four-fifths of this time, or 158 hours. No. 11 requires $11\frac{1}{2}$ miles of wind to start it, and will do no work during this time. The velocity is 11 to 15 miles per hour for 157 hours during the month. No. 3 will work all of this time, and No. 11 about nine-tenths thereof, or 141 hours. Both mills are running for all higher velocities. Mill No. 3 will run (if in the wind) about 75 per cent of the time at this place, and No. 11 about 51 per cent of the time.

Comparative performance of two mills.

Velocities.	Mill No. 3.			Mill No. 11.		
	Hours.	Power.	Product.	Hours.	Power.	Product.
6–10	158	0.067	10.6	0	0.0	0.0
11–15	157	.168	26.4	141	.19	26.8
16–20	109	.230	25.1	109	.40	43.6
21–25	72	.277	19.9	72	.56	40.3
26–30	34	.308	10.5	34	.63	21.4
31 and upward	22	.320	7.0	22	.64	14.1
Sum			99.5			146.2

Columns 2 and 5 of the above table give the number of hours during the mean month that each mill was running with a wind velocity of from 6 to 10, etc., miles per hour. Columns 3 and 6 give the horsepower for the mean velocity; for example, 0.168 is the horsepower for No. 3 at 13 miles per hour, and 0.19 is the horsepower for No. 11 for the same velocity. Columns 4 and 7 give the product of the number of hours and horsepower that each mill is yielding during the month. It is seen that No. 11 is doing 31 per cent more useful work than No. 3. If this comparison is made for the month of August, it will be found that No. 11 will do 26 per cent more useful work during this month than No. 3.

POWER MILLS.

The working parts of Power Mill No. 27 are shown in fig. 22. Instead of the reciprocating motion of the pumping mill, there is here a central shaft which is caused to rotate by beveled cog wheels. The sizes of the cog wheels are so taken that this central shaft makes six revolutions to one of the wind wheel. The pumping mill being back geared $3\frac{1}{3}$ to 1, and the power mill being geared forward 6 to 1, the vertical shaft makes twenty revolutions to one stroke of a pump worked by a pumping mill whose wind wheel is running at the same rate as that of a power mill. At the lower end of this shaft is a foot gear, shown in fig. 23, on which is placed the pulley which runs the grinder or other machine.

The power that a windmill is capable of developing can be determined better from a power than from a pumping mill, because the efficiency of the pump, which may be anything from 20 per cent to 85 per cent, is eliminated, and because the load on the mill can be varied at will, and thus the effect of load on the power can be determined for different wind velocities. To measure the power of this mill a pulley $9\frac{1}{2}$ inches in diameter was fitted to the shaft at A, fig. 23, and a Prony friction brake, having an arm about 3 feet long, made to fit the pulley. A spring balance reading to quarters of a pound was made fast at one end, the other end being fastened to the arm of the brake. The speed of the shaft was found to be too great to be taken by a recorder, so a speed counter was used. By turning the nuts on the under side of the brake the spring balance could be made to read any desired number of pounds, and thus the load on the mill could be regulated. By holding the speed counter on the end of the shaft, throwing it in gear at the beginning of a mile of wind and throwing it out of gear at the end of the mile, the number of revolutions of pulley was found. The time of making the mile was also noted, from which wind velocity was found. If u equal the number of revolutions of pulley per mile of wind, L the load as shown by spring balance plus load of arm, and R the length of brake arm, we have the number of foot-pounds per mile of wind: Foot-pounds$=\mathrm{L}\,u\,2\,\pi\,\mathrm{R}$.

In fig. 27 are given four curves showing the relation between the number of foot-pounds per mile of wind and the wind velocity for four loads, namely, 6 pounds, 4 pounds, 2 pounds, and 0 pounds. These curves are constructed in the same way as those of figs. 4, 8, 9, 11, 13, 15, 16, 18, and 20, by drawing a smooth curve among a series of points whose ordinates are found from the above equation and whose abscissas are the observed velocity of wind, so as to have about as many points on one side as on the other. The left, or steep part, of each curve is the most difficult to determine, and has a less degree of accuracy than the rest of the curve; owing to the velocity being low, several minutes are necessary to make a mile, and the wind may vary considerably during this time. It may be nearly an average all the time and the mill scarcely move, or it may be twice as rapid the latter half of the time as the first half, and the number of revolutions for the same mean velocity will be quite different in the two cases.

Another reason why the steep part is less accurate is that a very little movement to the right or left of this portion will change the number of foot-pounds much more than in any other part of the curve. The curve A B is for no brake load. The brake was off the pulley; no useful work was being done, but the resistance of the moving parts of the mill was being overcome. The pull necessary to overcome this resistance was found by standing on the platform of the mill and pulling the wind wheel around at uniform low speed with a spring balance. This was checked by winding a cord round the circumference of the wind wheel, and, standing on the ground, moving the mill when there

FIG. 27.—Diagram showing useful work for different loads of Mill No. 27.

was no wind by pulling on the spring balance attached to this cord. A pull of $1\frac{1}{4}$ pounds applied at the circumference (6 feet from center of wind wheel) was sufficient to overcome this resistance at a low velocity. Since the brake pulley is geared forward 6 to 1, the number of foot-pounds per revolution of brake pulley necessary to overcome this resistance is 7.9. The number of foot-pounds per mile of wind for other velocities is then easily found from speed of brake pulley.

The greater part of this curve, A B, fig. 27, is seen to be a nearly horizontal straight line, the number of foot-pounds per mile of wind required to run the machinery being nearly constant. The other three curves of this plate are for useful work only; the useless work is not included in them. The highest point of these curves is seen to rise and move to the right as the load increases, and the part to the right of the highest point is seen to become more and more steep as the load increases. A broken line, A K, has been sketched tangent

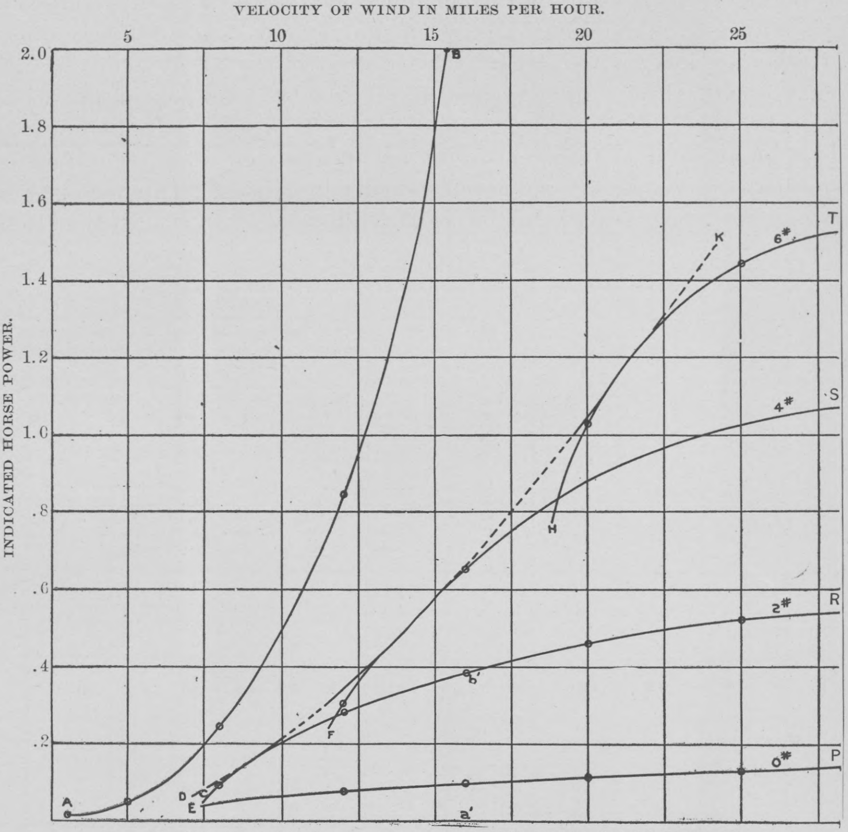


FIG. 28.—Diagram showing horsepower for different loads of Mill No. 27.

to these curves. It is the envelope of them and is concave to the horizontal coordinate axis. It would give the relation between foot-pounds per mile of wind and wind velocity if the load could be increased as the velocity increases.

Fig. 28 shows the relation between the horsepower and the wind velocity for the four loads—6 pounds, 4 pounds, 2 pounds, and 0 pounds. They are obtained from the curves of fig. 27 by reducing foot-pounds per mile of wind to horsepower; that is, for any velocity of, say, 16 miles per hour and load of, say, 2 pounds, divide the ordinate a b, fig. 27, by $\frac{60}{16}$ (the number of minutes required to make the mile), and by 33,000, and we have the corresponding ordinate a′ b′ of fig. 28.

It is seen from these curves that for any brake load the power of the mill increases rapidly as the wind velocity increases, and reaches a maximum for some velocity greater than 30 miles per hour. As the load increases, the velocity required to start the mill increases rapidly and the curve becomes more steep. For a given wind velocity the power increases rapidly as the load increases. For a velocity of 30 miles the power is nearly proportional to the load for loads less than 6 pounds. It is seen that when the velocity is less than 12 miles a 4-pound load is too great, and when the velocity is less than 19 miles a 6-pound load is too great. The dotted curve D K, which is the envelope of these curves, gives the relation between power and wind velocity for a constantly increasing load. It is seen that there would be a great saving of power by the use of a device which would automatically increase the load as the velocity increases. The horsepower would then be given by the curve D K, instead of by one of the other curves.

Results of computations of power mills.

Mill No.	Name.	Owner.	Size.	Brake load.	Foot-pounds per mile of wind when hourly velocity in miles is—					
					8	12	16	20	25	30
			Ft.	*Lbs.*						
26	Perkins	Geo. Gilbert	14	6	-------	-------	-------	-------	-------	-------
27	Aermotor	E. C. Murphy	12	6	-------	-------	-------	101,500	115,000	104,200
27	do	do	12	4	-------	50,000	80,800	88,400	80,800	71,700
27	do	do	12	2	22,000	47,000	47,800	45,400	41,400	35,600
27	do	do	12	0	12,000	12,000	11,400	11,000	10,200	9,700

Mill No.	Brake load.	Foot-pounds per minute when hourly wind velocity in miles is—						Useful work in horse power when hourly wind velocity in miles is—						Vane area in square feet.
		8	12	16	20	25	30	8	12	16	20	25	30	
	Lbs.													
26	6	-------	-------	-------	-------	-------	-------	-----	-----	.313	.609	.937	-----	100.2
27	6	-------	-------	-------	33,833	47,917	52,100	-----	-----	-----	1.028	1.451	1.576	72.9
27	4	-------	10,000	21,530	29,367	33,667	35,850	-----	.303	.653	.890	1.020	1.086	72.9
27	2	2,933	9,400	12,747	15,133	17,250	17,800	.089	.285	.386	.458	.523	.540	72.9
27	0	1,600	2,400	3,040	3,667	4,250	4,850	.050	.073	.087	.111	.128	.151	72.9

TOTAL ENERGY OF THE WIND.

The curve A B shows the relation between wind velocity and the total horsepower possessed by the wind at the temperature of 46° F. and the barometric pressure of 28.9 inches. It is found from the relation Horsepower $= \frac{w}{2g} A \frac{V^3}{550}$ where w is the weight per cubic foot of air at this temperature and pressure, A the vane area equals 72.9

square feet, V the velocity of wind in feet per second, and g the acceleration of gravity. w was found from the formula $w = \frac{T_0}{p_0} w_0 \frac{p}{T}$,[1] in which $T_0 = 273°$ C., $w_0 = .0807$ pounds per cubic foot, $p_0 = 14.7$ pounds per square inch, $T = 281°$ C., $p = 28.9$ inches, and C = the temperature expressed in centigrade degrees. Substituting these values, Horsepower = $.00021\ V^3$.

EFFICIENCY OF MILL.

By dividing any ordinate of a load curve by the corresponding ordinate of this curve A B, we have the efficiency of the mill for this load and velocity of wind. It is easily seen that the efficiency increases as the velocity decreases and as the load increases. The maximum efficiency is given by the ratio of the ordinate of the dotted curve to the corresponding ordinate of curve A B. This efficiency for a load of 2 pounds and a velocity of 9 miles per hour is 40 per cent, using as wind area the sum of the areas of the fans. At 14 miles with a load of 4 pounds it is 36 per cent. If the load at this velocity be reduced to 2 pounds the efficiency is reduced to 24 per cent.

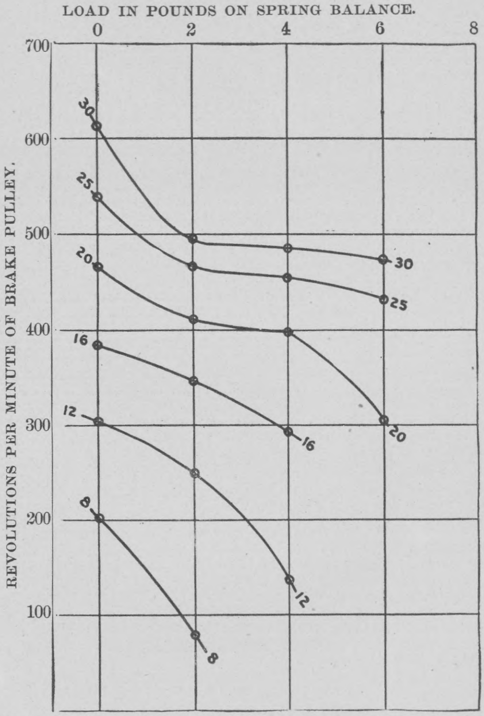


FIG. 29.—Diagram showing relation between number of revolutions of brake pulley per minute and load for different wind velocities for Mill No. 27.

Fig. 29 shows the relation between load and number of revolutions of the brake pulley for velocities of 8, 12, 16, 20, 25, and 30 miles per hour. It shows how much the speed is reduced by a given change of load. It is seen that for a velocity of 8 miles per hour changing the load from 0 to 2 pounds reduces the speed 60 per cent. When the velocity is 12 miles, changing the load from 0 to 2 pounds reduces the speed about 17 per cent, and changing from 2 to 4 pounds reduces it nearly 50 per cent. When the velocity is 16 miles, changing the load from 0 to 2 pounds changes the speed very little. When the velocity is 20 miles, the speed remains about constant for 2 and 4

[1] I. P. Churche's Mechanics of Engineering, p. 611, John Wiley & Sons, New York. Table giving results of computations of power mills.

pounds; at 25 and 30 miles the speed remains nearly constant for loads from 2 to 6 pounds.

MATHEMATICAL RELATION BETWEEN WIND VELOCITY AND POWER.

The relation between wind velocity and power of windmill is expressed graphically by the curves of fig. 28. The mathematical expression of this relation is given by Mr. A. R. Wolff on page 30 of his book, The Windmill as a Prime Motor, as Lv (or foot-pounds per second) $= \frac{s\,k\,c^2\,d}{g}\,v\left(\sin\alpha - \frac{v}{c}\cos\alpha\right)\cos\alpha$, where v=velocity of fan, s=surface of fan in feet, c=velocity of wind in feet per second, L=useful wind pressure on fan, d=density of wind, g=acceleration due to gravity, k is a coefficient, and α=the angle that the wind makes with surface of fan. It is seen that for a given wind velocity, density of air, and wind area, this expression for useful work is a function only of the velocity of the moving fan; it is not a function of the load on the mill. Fig. 29 shows that for a wind velocity of 30 miles per hour, and with a nearly constant velocity of wind area (v in the above formula), the load can be more than double, and thus the power more than doubled. It is evident, then, that however well this formula may give the power of the old Dutch mill or other modern mills not back geared, it gives results very much in error for a steel back-geared mill. Judging from the results of these tests, a formula giving the power of a steel back-geared mill should contain a factor which varies as the load on the mill varies.

GENERAL CONCLUSIONS.

1. The pumping power of windmills, or the useful work they do when raising water with reciprocating pumps of sizes from 4 to 10 inches diameter, is small—not greater that 0.65 of 1 horsepower for 12-foot mills, and much less than that claimed for them by some windmill makers.

2. The pumping power of windmills made for irrigating purposes is much greater than that of those which have been used for raising water for stock purposes.

3. The pumping power of the steel back-geared mills is greater than that of the wooden mills working with direct stroke.

4. The power of the Jumbo mill is much less—except for very high wind velocities—than that of the steel back-geared mills.

5. Well points produce a greater load on a windmill for a given lift and quantity of water than open wells.

6. Perhaps the most important result shown by these tests, and one that has not been clearly shown before, as far as the writer has seen,[1]

[1] Abstract of paper on "Windmills for raising water," by J. A. Griffiths: Proc. Inst. Civil Eng., Vol. 119, 1895, p. 15.

is the influence of load on mill, or number of foot-pounds per stroke of pump on the power of a mill. The influence of this load factor on the power can be seen by comparing the power of two pumping mills of the same diameter whose loads differ considerably; but it is much better shown by the tests of Power Mill No. 26. These tests show that for high velocities—25 or 30 miles—the power is very nearly proportional to the load on the mill. For 30 miles per hour, a brake load of 2 pounds gave 0.54 horsepower; a 4-pound load, 1.09 horsepower; and a 6-pound load, 1.55 horsepower. The influence of this factor on the power is so great that if it is not properly taken into account, it obscures the influence of resistance of well points and the working of valves of pump or the efficiency of the pump.

7. Another fact brought out by these tests, and which follows as a result of the previous ones, is that there should be some automatic device for increasing the load on a mill as the wind velocity increases. When the velocity is low—say 6 miles per hour—the load should be small enough to enable the wind wheel to run at a rapid rate—the rate for maximum power—and then as the wind velocity increases the load should be increased, so as not to allow the wheel to run at a higher speed. This is a very promising field for the inventor.

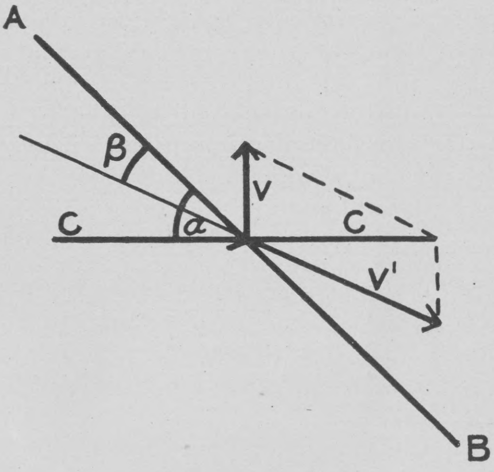


FIG. 30.—Diagram of forces acting on vane of mill.

8. If the load can not be automatically increased as the wind velocity increases, then the question arises, What is the proper or most economical load? This depends on the velocity of the wind each month at the given place. During the months of July and August there are a greater number of hours of low wind velocity than during any other two months of the year. The load should be light during these months for the greatest power. If the wind velocity is known, and the mill is one of the sizes and makes shown in the diagrams, the proper load can easily be computed. The mills in the vicinity of Garden, Kansas, would do more useful work if more heavily loaded.

It is seen that the useful work that a windmill will do when working under a constant load at all velocities is small, the horsepower varying as the first power of the velocity. By some device for automatically increasing the load as the wind velocity increases, the power may be much increased at high velocities, and will then vary as the second power of the velocity. Even with this device for increasing power there is still a great difference between the power possessed by the wind and the power developed by the mill, and this difference increases as the velocity increases.

The reason why the windmill utilizes so small an amount of the energy of the wind may be seen from the following: Let A B, fig. 30, be a strip taken from the outer end of one fan of a windmill. It is curved, but for this purpose it may be considered a plane. This strip makes an angle α with the absolute direction of the wind. C represents the amount and direction of the wind; V represents the amount and direction of the velocity of the surface A B. Then the relative velocity of the wind—that is, its velocity with respect to the moving surface A B—is V', the diagonal of the parallelogram constructed on V and C as sides, V' makes an angle β with the sloping surface A B. If $V=0$—that is, if the wheel is held so that it can not revolve—the angle $\beta=\alpha$. As V increases β grows less and less, and finally becomes zero, in which case V' is parallel to surface A B. In this case the surface receives no pressure from the wind—this portion of the fan is not utilizing any of the energy of the wind. If V be still further increased, β becomes negative, and the wind pressure is on the opposite side of A B. This portion of the fan is then doing work on the wind instead of the wind doing work on the fan. The effective wind area of a fan being the projection of the fan on a plane at right angles to the relative velocity of wind over it—that is, to V'—it is seen that as V increases the effective wind area decreases. The energy which the fan takes from the wind is proportional to the effective wind area. It is seen, then, that this reduction of effective wind area is the reason why the efficiency is low at high velocities. If this effective wind area could be kept constant by some device for changing the angle of the fans, the relation between wind velocity and horsepower might vary nearly as the third power of the wind velocity.

In this discussion we have not taken into account the reduction of wind area due to the wind wheel swinging out of the wind, or "regulating." The mill can be built strong enough so that it will not need to regulate for velocities less than 30 miles an hour.

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